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COLLISION AVOIDANCE GROUND STATION ANALYSIS

John L. Mohr

McDonnell Douglas Electronics Company

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16. Abstract

Three different collision avoidance system (CAS) analyses were performed; ground station clock requirement, Loran-C accuracy and comparisons, and CAS monitoring requirements. Cesium beam standards are evaluated to determine their time accuracy, the number required to attain and maintain time to within 0.5 μs, 3σ.

The Loran-C system is reviewed to determine the potential time accuracy attainable by monitoring the Loran-C transmission. The results are then compared to the accuracy attainable from satellite, television, WWV and WWVB time transfer.

The CAS equipment has certain built-in tests. These tests, as well as additional external monitors, are reviewed to categorize the test type and effectiveness.

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1.0 INTRODUCTION

This report presents the results of the CAS ground station analysis developed under contract DOT-FA73WA-3239. The analysis is divided into three independent sections:

(1) Ground Station Clock Requirements;

(2) Loran-C Accuracy and Comparison to Other Time Dissemination Services; and

(3) CAS Monitoring Requirements.

The purpose of the first section is to determine the clock characteristics necessary to support the requirements of FAA ER-240-016 for time accuracy of 0.5 microseconds, 3 sigma. The analysis shows:

(1) The HP5061A-01 clock can maintain time to within 0.5 μs, 3σ for about 5 days;

(2) If option 4 is added to the HP5061A-01, the time is increased to about 38 days;

(3) Timekeeping capability is improved inversely proportional to the number of clocks used; and

(4) Accurate time can be maintained with three cesium beam standards, or two plus a Loran-C receiver, plus a failure monitor which includes automatic switchover.

The purpose of the second section is to determine the time accuracy attainable by monitoring Loran-C transmissions and to compare Loran-C time accuracy with other time dissemination services such as satellite, television, WWV and WWVB. The results of this analysis are:

(1) The absolute time accuracy of the Loran-C signals is about 0.7 μs,3σ;

(2) Relative time accuracy, two receiving stations listening to the same transmission, can be within 0.1 μs, provided the signal propagation paths are highly correlated;

(3) Loran-C accuracy is better than WWV and absolute TV accuracy; and

(4) Relative TV time accuracy, and satellite time accuracy are better than absolute Loran-C time accuracy and comparable to relative Loran-C time accuracy.

The purpose of the third section is to determine the CAS monitoring requirements in terms of type of test/monitoring tests included in the CAS equipment, level of degradation which causes a CAS alert, and testing the CAS signal in space. The results of this analysis are that the tests/monitoring included in the CAS design provide reasonable assurance of rapid failure detection and fault isolation.

2.0 GROUND STATION CLOCK REQUIREMENTS ANALYSIS

The objective of this analysis is to establish the requirements for ground station clocks in order to support the requirements of FAA ER-240-016 for time accuracy of 0.5 microseconds (μs), 3 sigma (σ). Three aspects of clock requirements are analyzed herein: (1) accuracy and merits of portable clock synchronization, (2) accuracy and numbers of cesium clocks, and (3) clock redundancy and monitoring. A general time error equation is developed in the first section. The equation is then used to establish the standard deviation of the time error as a function of initial time errors and elapsed time since synchronization assuming a portable clock is used as the initial time reference. The analysis shows that an HP5061A-01 can maintain time to within 0.5 μs, 3σ for about five days; if option 4, the improved beam tube, is used, the time is increased to about 38 days.

In the second section, the general equation is used to evaluate the effects of using multiple clocks to maintain time. Five different time reference sources are considered in conjunction with multiple clocks; Loran-C, satellite, portable clock, television, and WWV. The analysis indicates that time keeping capability is improved by using multiple clocks. The errors are inversely proportional to the square root of the number of clocks; therefore, the greatest percentage reduction is with the first few clocks. The long term time keeping capability is essentially independent of the time reference used for initial time transfer.

The last portion of this analysis determines the number of clocks, and required monitoring to maintain time to within 0.5 μs, 3σ with a high availability. The analysis shows that accurate time can be maintained with three frequency standards (3 cesium beam or 2 cesium beam plus Loran-C) and automatic switchover.

2.1 ACCURACY AND MERITS OF PORTABLE CLOCK SYNCHRONIZATION

The objective of this section of the analysis is to review the accuracy and relative merits of portable clock type synchronization technique. This technique has been used by the USNO, United States Naval Observation, for several years to disseminate time to various military bases and national observatories. The USNO certifies time accuracy to within ± 0.2 us provided the closure is good (Winkler, Ref. 1). This analysis confirms the feasibility of 0.2 us or better synchronization with portable clocks.

2.1.1 General Analysis

The time accuracy attainable by clock is dependent upon three factors:

1. The initial setting of the clocks (synchronization accuracy)
2. The period between synchronization.
3. The confidence in the accuracy and continuity of operation between synchronization.

The clock, at time t, indicates a time, T, which consists of an initial time setting or synchronization, T_s, plus the time integral of the scaling frequency, f; or

$$T = T_s + \int_0^t \frac{f(T)\, dT}{f_o} \qquad (2\text{-}1)$$

Where T_s is the time of initial, or last, synchronization,

and f_o is the standard frequency for which the clock was designed to scale time.

The difference between this time T and the time at some new time can be written:

$$T - t = T_s - t + \int_0^t \frac{(f(T) - f_o)\, dT}{f_o} \qquad (2\text{-}2)$$

rearranging, this becomes

$$\Delta T = \Delta T_s + \int_o^t \frac{\Delta f(T)}{f_o} \, dT \qquad (2\text{-}3)$$

where $\Delta T = (T - t)$ total clock error

$\Delta T_s = (T_s - t)$ fixed time error

$\Delta f(T) = (f(T) - f_o)$ frequency offset as a function of time

The frequency offset is approximated by an initial offset and a frequency drift rate, or

$$\Delta f(T) = \Delta f + \Delta f' \; T + \Delta f_m(T) \qquad (2\text{-}4)$$

where Δf = fractional frequency offset at synchronization time,

$\Delta f'$ = first order drift rate at synchronization time, assumed constant,

$\Delta f_m(T)$ = higher order and unpredicted errors such as may be caused by environmental changes

When equation (2-4) is substituted into equation (2-3) the clock error expression then becomes:

$$\Delta T = \Delta T_s + \frac{\Delta f \; t}{f_o} + \frac{\Delta f' \; t^2}{2 \; f_o} + \Delta f_m \qquad (2\text{-}5)$$

The synchronization error, T_s, can be apportioned to initial source error, ΔT_i and the transfer or resynchronization error ΔT_r. This situation occurs if the resynchronization is dependent upon a calibration procedure performed at the time of a prior synchronization. The final expression for ΔT is in the same form as generally used for clock analysis (Reder and Winkler, Ref.2).

$$\Delta T = \Delta T_i + \Delta T_r + \frac{\Delta ft}{f_o} + \frac{\Delta f' t^2}{2 \; f_o} + \Delta f_m \qquad (2\text{-}6)$$

These errors are usually expressed in terms of their variances. Assuming these terms are statistically independent, the variance can be expressed:

$$\sigma_t^{\;2} = \sigma_i^{\;2} + \sigma_r^{\;2} + \sigma_f t^{\;2} + \frac{\sigma_{f'} \; t^2}{2}^{\,2} + \sigma_m^{\;2} \qquad (2\text{-}7)$$

σ_t = standard deviation of time error after time interval t,

σ_i = standard deviation of the time source error used as a reference (ΔT_i)

σ_r = standard deviation of the error in transferring time to portable clock (ΔT_r)

σ_f = standard deviation of the fractional frequency difference ($\Delta f_i/f_o$)

$\sigma_{f'}$ = standard deviation of frequency drift ($\Delta f'/f_o$)

σ_m = standard deviation of unpredicted perturbation (Δf_m)

2.1.2 Error Budget

The magnitude of each uncertainty term from 2-7 is listed in Table 2-1. The values for both the HP5061A-01 clock and the HP5061A-01 clock with option 4 are listed.

TABLE 2-1 STANDARD DEVIATIONS

TERM	STANDARD DEVIATION SOURCE: HP5061A	STANDARD DEVIATION SOURCE: HP5061A With Option 4	COMMENT
σ_i	0	0	Assuming source is USNO and USNO time error is negligible
σ_r	$5x10^{-9}$ sec	$5x10^{-9}$ sec	Limited by clock jitter (HP Clock Specification)
σ_f	$3.5x10^{-13}$, for $t>7.1x10^{-4}$ sec $8x10^{-11}/t$ for $t<7.1x10^{-4}$ sec	$5x10^{-14}$	Assuming σ_f is half of clock settability (HP specification)
$\sigma_{f'}$	0	0	No long term drift (HP clock specification)
σ_m	$1x10^{-8}$ sec	$1x10^{-8}$ sec	Arbitrarily assigned

2.1.3 ͻr Calculation

The uncertainties from Table 2-1 are entered into equation 2-7 both for the basic clock and with option 4. Where t is in days and σ_t is in seconds,

HP5061A: $$\sigma_t^2 = (5 \times 10^{-9})^2 + (10^{-8})^2 + (7/2 \times 10^{-13} \times 86400t)^2 \quad (2\text{-}8)$$

HP5061A with option 4:

$$\sigma_t^2 = (5 \times 10^{-9})^2 + (10^{-8})^2 + (1/2 \times 10^{-13} \times 86400t)^2 \quad (2\text{-}9)$$

Each of these equations was evaluated both as shown and when all constant terms have been set to zero ($\sigma_l = \sigma_r = \sigma_m = 0$). This second evaluation demonstrates the effects of the time varying terms alone. The results have also been plotted in Figure 2-1. Note on this figure that the time uncertainty of the HP5061A is less than 0.5 μs, 3σ, for about 38 days. Figure 2-1 also shows that the time varying terms are the principal uncertainty terms after the first few days.

2.1.4 Time Transfer by Extrapolation

The third term of equation (2-9) is the primary term for t >> 1 day. The constant associated with this term resulted from an assumed worst case drift. However, if the portable clock is returned to the USNO for a time closure, an average time drift rate can be established and used to reduce the time transfer uncertainty. For example assume a portable clock has an accumulated time error as shown in Figure 2-2 and is sent on a 9 day time transfer mission without closure, Figure 2-1 applies and the 3σ uncertainty would be 0.9 μs. After a closure Figure 2-2 applies and the time uncertainty is less than 0.4 μs, 3σ. The USNO, using this approach, certifies time transfer to within ± 0.2 μs provided the closure is good. (Winkler, Ref. 1).

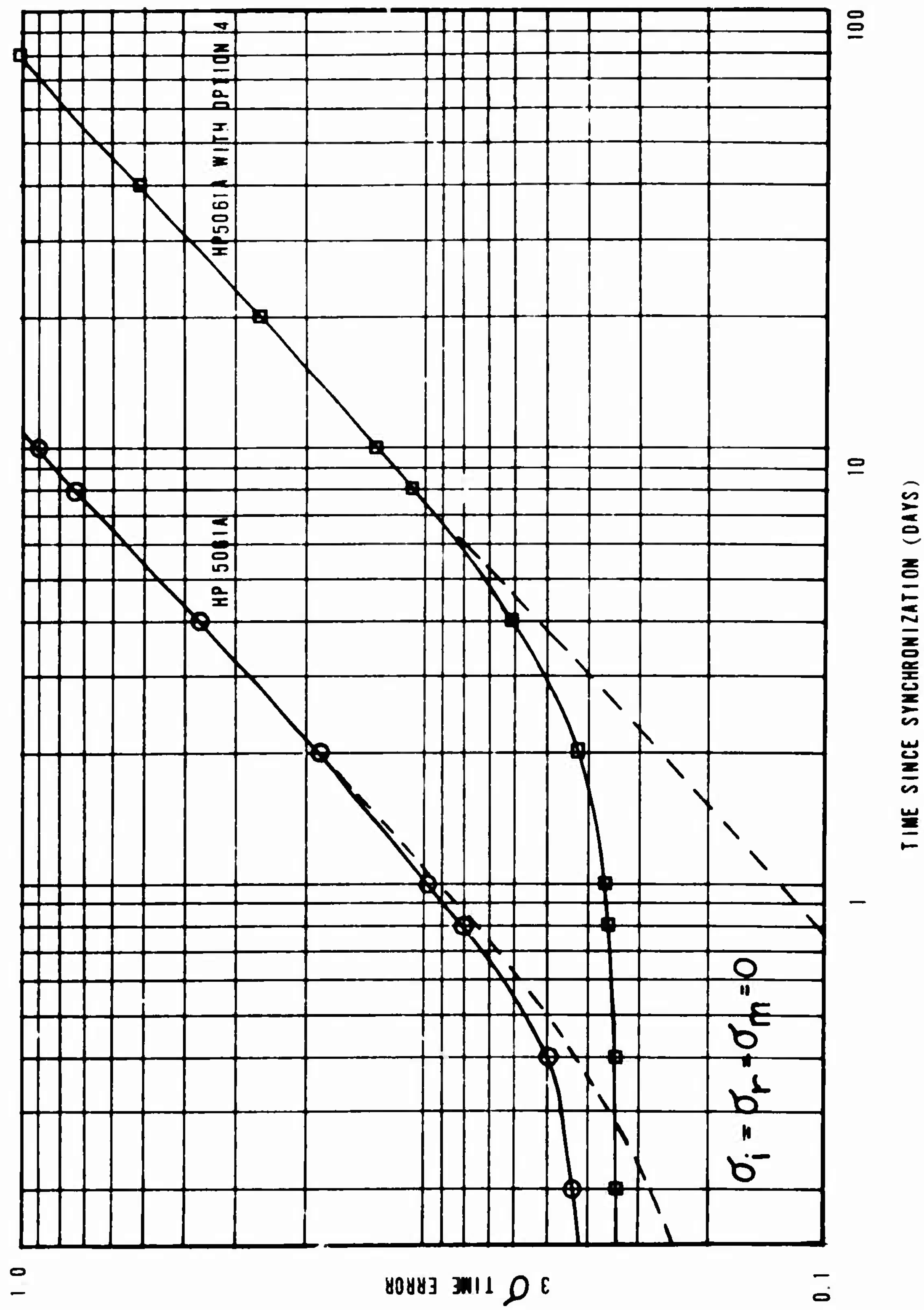


FIGURE 2-1 CLOCK ERROR VERSUS TIME SINCE SYNCHRONIZATION

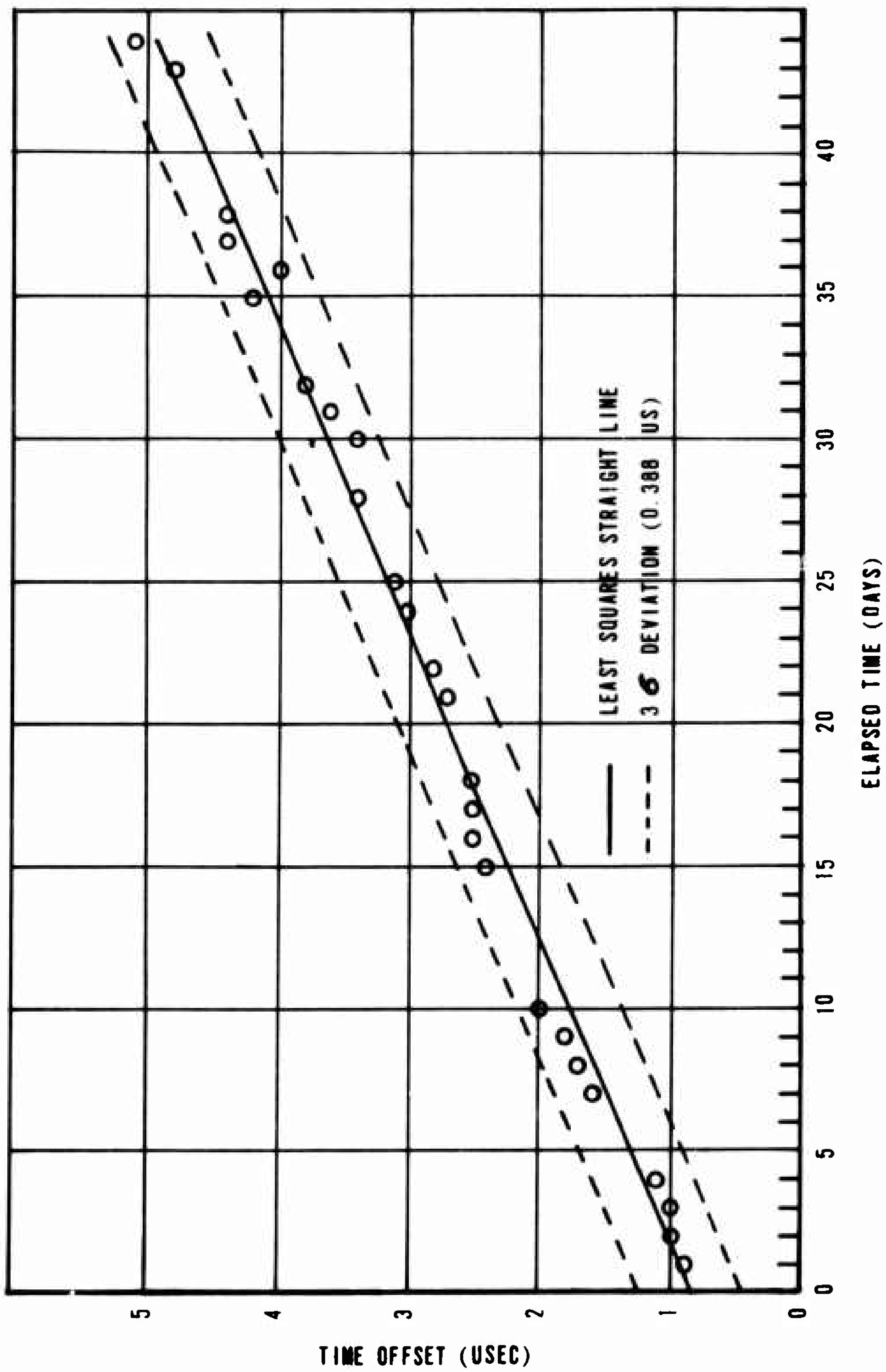


FIGURE 2-2 PORTABLE CLOCK TIME ERROR

2.1.5 Conclusion

Portable clock type synchronization can provide sufficient accuracy to support the requirements of FAA ER-240-016 provided (1) the elapsed time to transfer is short or (2) the clock frequency offset remains relatively constant during the synchronization mission.

2.2 ACCURACY AND NUMBERS OF CESIUM CLOCKS

This analysis is in accordance with the requirements of FAA-ER-240-016 paragraphs 1.2.3a and 3.1 (a) (4). The HP5061A clock and the HP5061A clock with improved beam tube (Option 4) are analyzed to determine the number of clocks and their ability to maintain a required time accuracy of 0.5 μs, 3σ.

A single HP5061A clock can maintain time with an uncertainty 0.5 μs, 3σ for about 5 days depending upon the accuracy of the time transfer source. If Option 4 is used, the time period is extended to about 38 days. Multiple clocks reduce the random time uncertainties inversely proportional to the square root of the number of clocks but do not affect systematic errors.

2.2.1 General

Time accuracy at any time after synchronization is a function of the synchronization error, clock drift rates, time since synchronization; and the number of clocks being used. The time uncertainty was expressed in paragraph 2.1 as

$$\sigma_t^2 = \sigma_i^2 + \sigma_r^2 + \left(\sigma_f\, t\right)^2 + \left(\sigma_{f'}\, \frac{t^2}{2}\right)^2 + \sigma_m^2 \qquad (2\text{-}10)$$

The constant terms establish the initial error and are essentially independent of the clock. The time varying terms are dependent upon the quality of the clock.

2.2.2 Error Budget

The magnitude of the σ_i term from (1-10) is determined by the accuracy of the time reference used. Paragraph 3 analyzes five different time transfer systems. These systems and their associated σ_i value are as follows:

(1) portable clock, $\sigma_i = 0.07$ microseconds (μs);
(2) Loran-C, $\sigma_i = 0.23$ μs;
(3) television, $\sigma_i = 1$ μs;
(4) satellite, $\sigma_i = 0.1$ μs; and
(5) WWV, $\sigma_i = 4.0$ μs.

These values for σ_i were obtained from paragraph 3.

Resynchronization uncertainty, σ_r, is determined either by the instrumentation measurement capability, by the clock's pulse to pulse jitter, or a combination thereof. The clock pulse-to-pulse jitter is 5 nanoseconds (ηs), 1 σ. This is significantly greater than the equipment capability so $\sigma_r = 5$ ηs. The term σ_m is included to cover the possibility of an unpredictable time error; is arbitrarily assigned a value of 10 ηs.

The two remaining terms are strictly a function of the quality of the frequency source. The basic HP5061A clock and HP5061A with Option 4 are considered herein. The standard deviation of each error associated with each clock is shown in Table 2-2.

TABLE 2-2 TIME UNCERTAINTIES

TERM	MAGNITUDE
σ_i	0.07 (portable clock), 0.23 (Loran-C), 1.0 (TV), 0.1 (Satellite): 4.0 (WWV)
σ_r	0.005 μs (HP specification)
σ_m	0.01 μs (arbitrarily assigned)
σ_f	$8 \times 10^{-11}/\sqrt{t}$ for $t \leq 7.1\ 40^4$ sec; 3.5×10^{-13} for $t > 7.1 \times 10^4$ sec. (HP5061A)* 5×10^{-14} (with opt.4)*
$\sigma_{f'}$	0 (HP specification for long term stability)

* Assuming standard deviation is half of clock settability.

The σ_i terms for TV and WWV, 1 μs and 4 μs respectively (from Table 2-2) are too large to provide accurate time transfer. Therefore, only Loran-C, satellite and the portable clock are analyzed further. Equation 2-10 was evaluated for eight different conditions: four conditions with each clock. The conditions were $\sigma_i = 7 \times 10^{-8}$ seconds, $\sigma_i = 1 \times 10^{-7}$ seconds, $\sigma_i = 2.3 \times 10^{-7}$ seconds, and $\sigma = \sigma_r = \sigma_m = 0$. The results of these calculations are plotted in Figure 2-3.

2.2.3 Discussion

The curves in Figure 2-3 demonstrate that for short periods of time, the constant terms establish the uncertainty; however, the quality of the frequency source eventually becomes the limiting factor. For example, using only the time varying terms of the HP5061A clock, the time uncertainty is less than 0.5 μs, 3 σ for about 5 days. If Option 4 is added to the clock, the 0.5 μs, 3σ time uncertainty can be maintained for about 38 days.

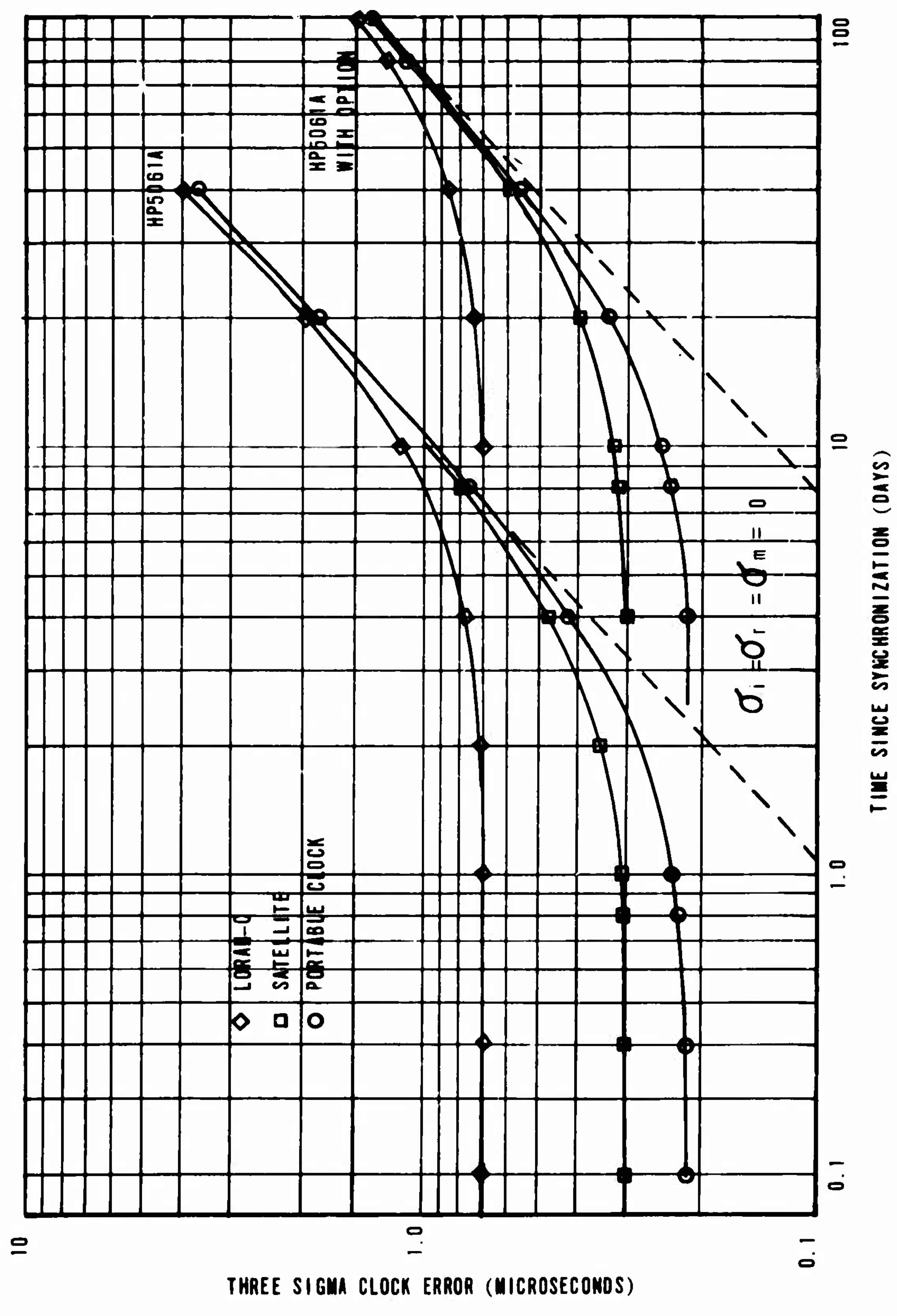


FIGURE 2-3 CLOCK ERROR WITH DIFFERENT INITIAL ERRORS

Updating, using a portable clock and the satellite time references can be used to maintain time to within 0.5 μs, 3σ. The absolute time accuracy of Loran-C is about 0.7 μs, 3σ. Its principal limitation is the propagation anomalies of 0.6 μs, 3α (Pakos, Ref. 3). As discussed in paragraph 2. the Loran-C propagation anomaly can be reduced if multiple stations can be monitored.

2.2.4 Multiple Clocks

If the outputs of multiple clocks of equal quality are averaged, the coefficients of the time varying terms can be reduced by $\sqrt{N}$ (Mosteller, et al, Ref. 4), where N is the number of clocks. However, it is essential that the clocks by physically separated to insure environmental independence. The USNO uses 6 different clock vaults (Winkler et al, Ref. 5) with independent controls. For multiple clocks, the uncertainty equation is modified to the form

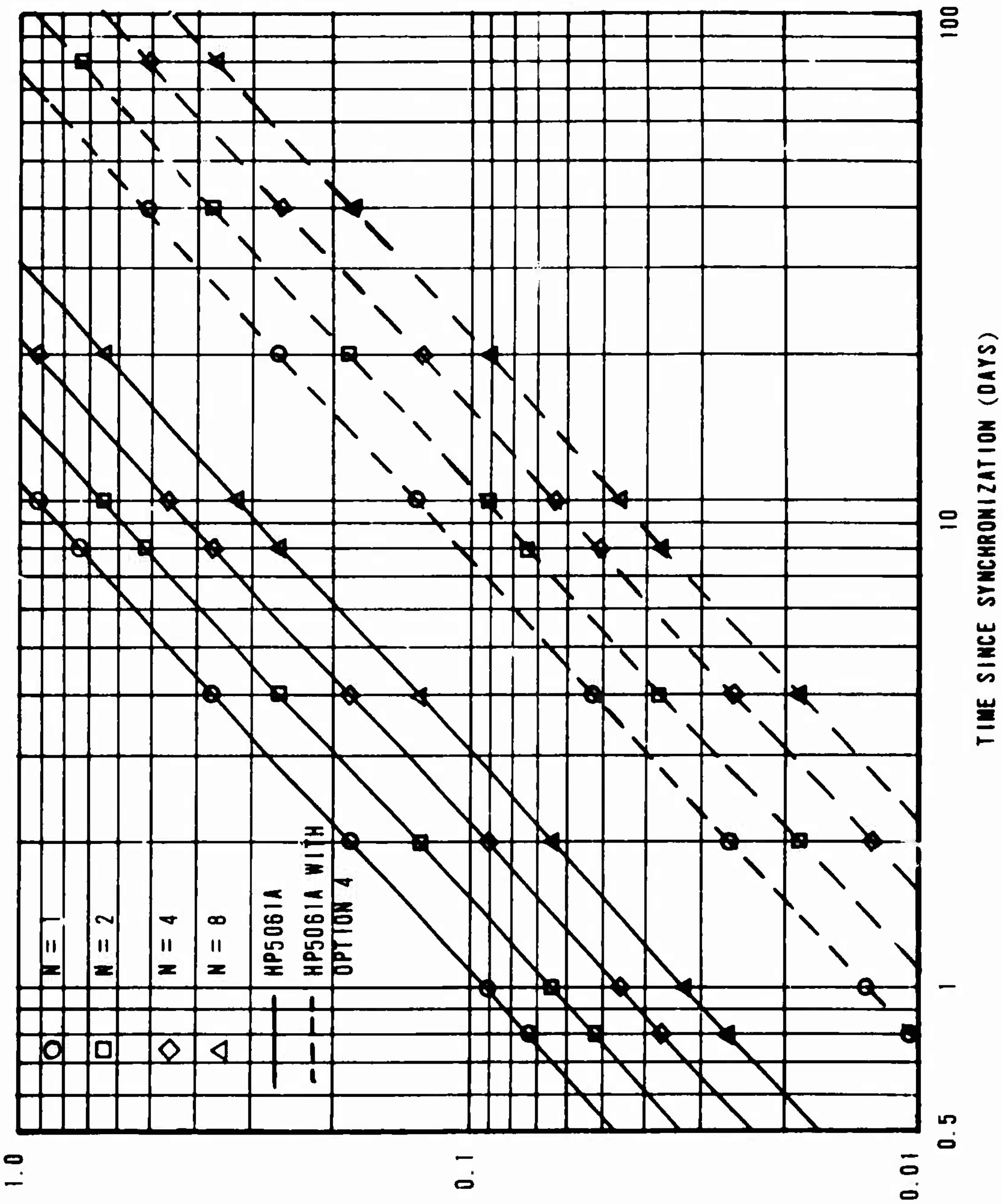
$$\sigma_t^2 = \sigma_i^2 + \left[\sigma_r^2 + \sigma_m^2 + \left(\sigma_f t^2 + \sigma_{f'} \frac{t^2}{2}\right)^2\right] \Big/ N \qquad (2\text{-}11)$$

This equation was evaluated with $\sigma_i = \sigma_r = \sigma_m = 0$. The results of the evaluation are plotted in Figure 2-4. The benefit of additional clocks reduces inversely proportional to the square root of the number of clocks being averaged.

In multiple clock timekeeping, the uncertainties may be averaged using either weighted or unweighted values of clock uncertainty. The USNO using a 15 clock ensemble has demonstrated a one sigma frequency offset of 4.4×10^{-13} (Ref. 4).

2.3.5 Conclusions

The standard time error deviation of the maintained by a clock is determined by the transfer reference source for short periods of time and



THREE SIGMA TIME ERROR WITH MULTIPLE CLOCKS (US)

FIGURE 2-4 ERROR REDUCTION USING MULTIPLE CLOCKS by clock offset and stability for longer periods of time. Multiple clocks can help maintain accurate time; the greatest percentage benefits obtained with the first few clocks.

2.3 CLOCK REDUNDANCY AND TIME MONITORING

The objective of this analysis is to determine the redundancy configuration of clocks and the level of time and frequency monitoring to achieve an acceptable level of confidence, reliability and availability of ground station time. Previous paragraphs have demonstrated that a single cesium beam clock can provide time within 0.5 μs, 3σ provided (1) the initial time transfer was accurate; and (2) the elapsed time since the transfer is not excessive. However, it is possible that during this elapsed time a perturbing phenomenon will cause a time error. Clock redundancy and time/frequency monitoring can be used to detect the effect of the perturbation and prevent a time error from being propagated to other systems.

2.3.1 General

The basic arrangement is a monitoring loop in which each frequency standard is compared to the others. An unfavorable comparison to one of only two contiguous standards is insufficient evidence of failure. Both comparisons unfavorable indicate a malfunction. In this arrangement, at least three standards are required.

Figure 2-5 is a conceptual block diagram. The output of the clocks and the receiver are compared in a triangular loop for self-analysis of a timing difference, which the monitoring logic detects. The Loran-C receiver serves a dual purpose of first evaluating the time dissemination through the Loran-C system, and second of representing a "third" cesium standard (the USNO master) in the self-monitoring loop.

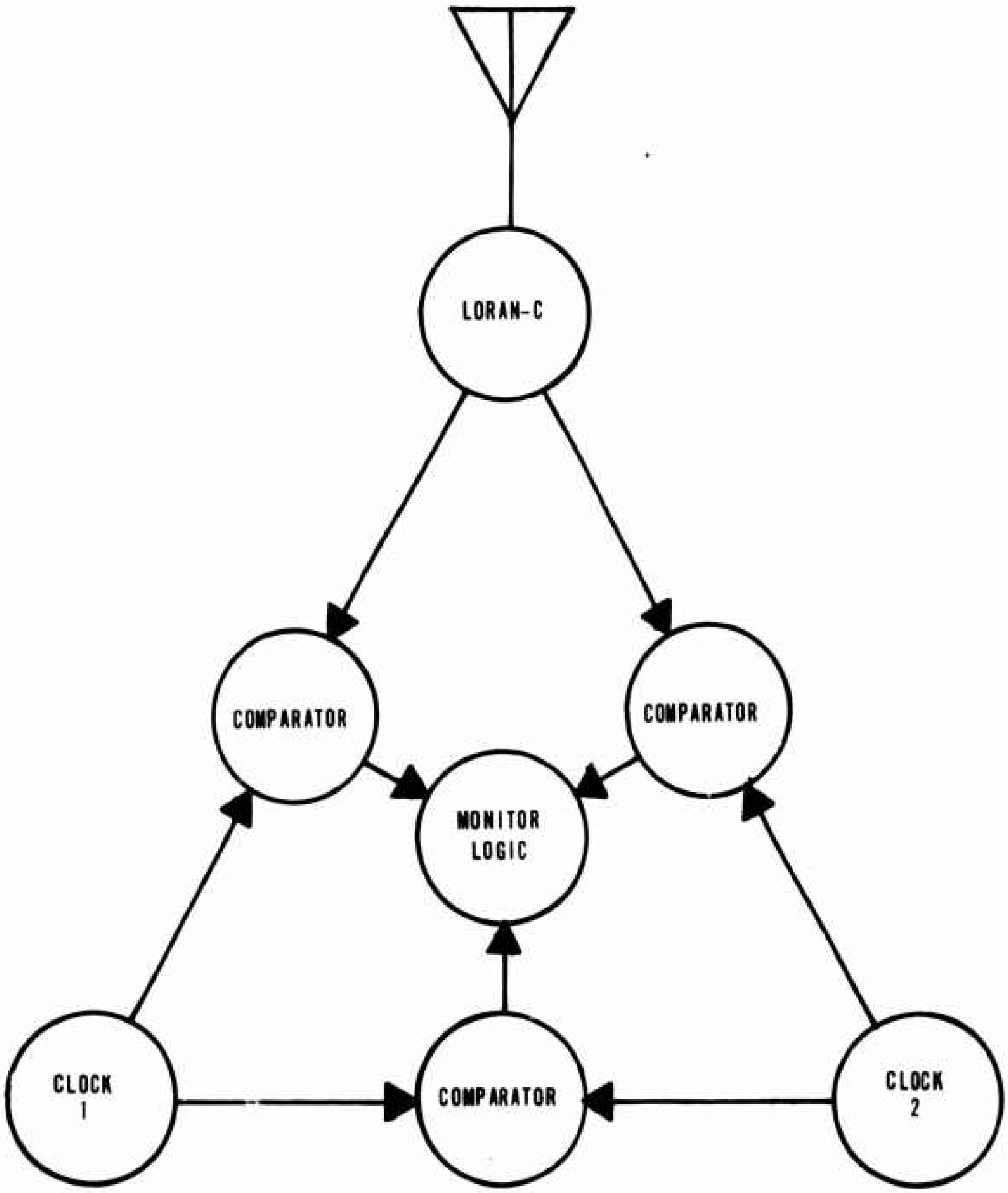


FIGURE 2-5 GROUND STATION CLOCK SUBSYSTEM

2.3.2 Clock Redundancy

The effects of multiple frequency standards upon time and frequency accuracy are analyzed in paragraph 2.2. The results demonstrate that random uncertainties can be reduced by averaging. However, using only two frequency standards does not increase confidence in time frequency accuracy unless the standards agree. If they disagree, there is no way to know which one is correct. Therefore, at least three standards are required to increase confidence level. This might be three cesium beam frequency standards or two cesium standards and a precise reference system such as Loran-C.

Analysis from paragraph 3.1 indicates that Loran-C has a time uncertainty of 0.2 to 0.3 μs, 1σ. The advantage using Loran-C as the third standard is that it is the best reference which is readily available. While its time accuracy does not meet the requirements of FAA-ER-240-016, using Loran-C can ensure that there are no gross time errors in the system. In addition, Loran-C can provide a frequency reference which is accurate to 2×10^{-12} (Austron, Ref. 6).

Assume that the basic clock subsystem consists of two cesium standards and a Loran-C receiver. System availability is a function of the mean-time-between-failure (MTBF) and mean-time-to replace (MTTR) (MIL-HDBK) 217A, Ref. 7).

$$A\ (\text{Availability}) = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \qquad (2\text{-}12)$$

For a two out of three unit reliability, the total MTBF can be derived from Figure 2-6 where the MTBF of series and parallel elements are considered separately (Ref. 7).

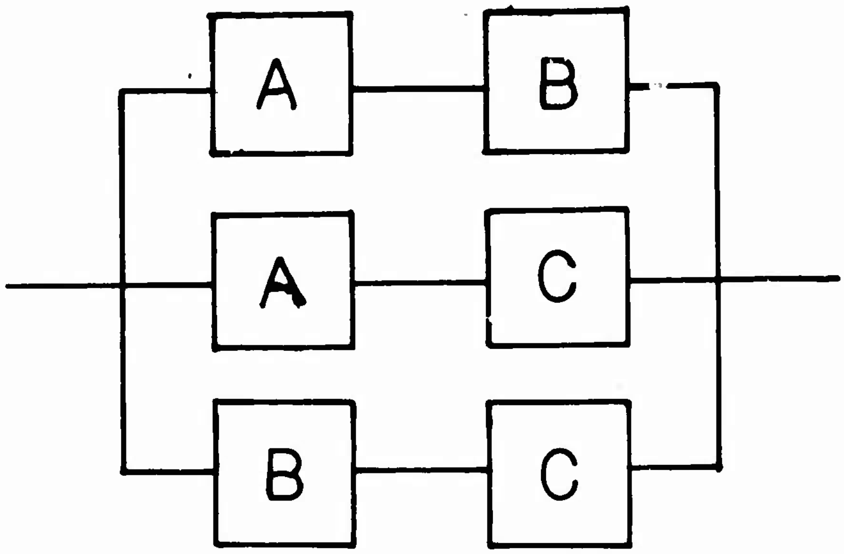


FIGURE 2-6 TWO OUT OF THREE RELIABILITY

The MTBF of each series pair is determined as follows:

$$MTBF_s = \frac{1}{\frac{1}{M_i} + \frac{1}{M_j}} = \frac{M_i \times M_j}{M_i + M_j} \tag{2-13}$$

The MTBF three parallel elements is expressed as follows (Bazovsky, Ref. 8):

$$M_T = M_{ab} + M_{ac} + M_{bc} - \frac{M_{ab} \times M_{bc}}{M_{ab} + M_{bc}} - \frac{M_{ac} \times M_{bc}}{M_{ac} + M_{bc}}$$

$$+ \frac{M_{ab} \times M_{ac} \times M_{bc}}{M_{ab} \times M_{ac} + M_{ab} \times M_{bc} + M_{ac} \times M_{bc}} \tag{2-14}$$

The MTBF of each cesium standard is 10,000 hours; the MTBF of the Loran-C receiver is 5,000 (empirical estimate from austron; there is no certified data available). Therefore,

M_{ab} = 5,000 hrs.; $M_{ac} = M_{bc}$ = 3,333.3 hrs.

$$M_T = 5{,}000 + 3{,}333.3 + 3{,}333.3 - 2{,}000 - 2{,}000 - 1{,}666.7 + 1{,}250 \tag{2-15}$$

The value of MTBF (4,750 hours) is entered into 2-12 along with the specified MTTR (FAA-ER-240-016, Ref. 9)

$$A = \frac{4{,}750}{4{,}750 + 0.5} \approx 0.999895$$

If one of the units fails, the new MTBF is either 5,000 hours or 3,333.3 hours depending upon whether the Loran-C receiver or a cesium standard failed.

If the failed unit is the Loran-C receiver, it can be removed for repair. The two cesium standards can maintain time and frequency for several days while the receiver is being repaired. If the on-line cesium standard has failed, it can be removed for repair as soon as it has been identified. The system becomes operational within six seconds upon identification and removal of the failed unit. The primary problem, therefore, seems to be one of monitoring and fault identification.

2.3.3 Monitoring

A set of monitoring logic is included in Figure 2-6. Several types of monitoring could be performed by such logic:

(1) compare the phase of the basic frequency;
(2) verify output frequency is present;
(3) compare the lengths and time of occurrence of message slots (1.5 ms), one second ticks, epoch (six second) ticks;
(4) identify the failed standard; and
(5) automatically switch from failed to operational standard.

The principal concern here is in fault identification and switch-over time. Table 2-3 lists these items which could be monitored along with an estimate of fault identification time. All of the monitor items listed therein are in units of time. Frequency differences could be monitored with separate equipment; however, it is simpler to monitor the effects of frequency difference; i.e., time difference. The longest fault identification time listed in Table 2-3 is about 6 seconds. It is apparent that fault identification time does not limit system availability.

TABLE 2-3 FAULT IDENTIFICATION TIME

Monitored Item	Identification Time	Comment
5 MHz	0.4 to 0.6 μs	No signal for 2 to 3 cycles.
1 MHz	1 to 3 μs	No signal for 2 to 3 cycles
5 MHz or 1 MHz voltage	1 sec.	Low signal level
Message Slot Length	1.5 ms	Time to count length of message slot
Differences in end of slot time	1.5 ms+1μs	Compare to time of occurrence
Difference in occurrence of 1 sec. tick	1 sec.+1μs	Time to count 1 sec. and compare differences.
Coincidence of 6 sec. ticks	6 sec.+1μs	Time to count 6 sec. and compare differences.

There are three basic types of clock failure to be considered: slow drift, step changes, and stoppage. Regardless of the cause, the indication from the comparison is that the clock is either on time, early, or late (t, t+1, or t-1). There are 27 possible combinations from these three terms as shown in Table 2-4, where the resulting comparison yields both magnitude and sign of disagreement. However, it is not necessary to determine magnitude and sign of the clock difference. Agreement or disagreement between each pair of clocks is adequate to take effective action. Therefore, Table 2-4 reduces to the eight terms indicated by asterisk and only three comparisons are required: coincidence of pulses A and B, A and C, and B and C. If the pulses from any pair of clocks are coincident, those clocks can be used for system operation. If one clock fails, the other two can be used as long as they are in agreement.

This discussion assumed that three cesium beam clocks were being used. There is no significant difference if one of the "clocks" is a Loran-C receiver. The principal difference is that for the first few days following a visit from a portable clock, Loran-C is less accurate than the cesium standards. During this time broader tolerances should be allowed. However, after one to five weeks, Loran-C becomes the most accurate reference. This turn of events is caused by the clock's long term drift.

2.3.4 Switchover

If a fault is detected by the monitoring circuits, the resulting action may be either automatic switchover or operator alert and manual depending upon the nature of the fault. For example, a low voltage on the 5 MHz would be an operator alert unless accompanied by other discrepancies. Failure of the off line clock would be operator alert; but failure of the on line clock would be cause for automatic switchover. When automatic switchover is required, it can be accomplished within two epochs of fault detection.

TABLE 2-4 THREE-CLOCK TIME COMPARISON

CLOCK READING			CLOCK DIFFERENCE			USEABLE
A	B	C	(A-B)	(A-C)	B-C)	CLOCKS
t-1	t-1	t-1	0	0	0	A, B, C
t-1	t-1	t	0	-1	-1	A, B
t-1	t-1	t+1	0	-2	-2	A, B
t-1	t	t-1	-1	0	+1	A, C
t-1	t	t	-1	-1	0	B, C
t-1	t	t+1	-1	-2	-1	None
t-1	t+1	t-1	-2	0	+2	A, C
t-1	t+1	t	-2	-1	1	None
t-1	t+1	t+1	-2	-2	0	B, C
t	t-1	t-1	1	1	0	B, C*
t	t-1	t	1	0	-1	A, C*
t	t-1	T+1	1	-1	-2	None
t	t	t-1	0	+1	1	A, B*
t	t	t	0	0	0	A, B, C*
t	t	t+1	0	-1	-1	A, B*
t	t+1	t-1	-1	1	2	None
t	t+1	t	-1	0	1	A, C*
t	t+1	t+1	-1	-1	0	B, C*
t+1	t-1	t-1	+2	+2	0	B, C
t+1	t-1	t	+2	1	-1	None
t+1	t-1	t+1	2	0	-2	A, C
t+1	t	t-1	1	2	-1	None
t+1	t	t	1	1	0	B, C
t+1	t	t+1	1	0	-1	A, C
t+1	t+1	t-1	0	2	2	A, B
t+1	t+1	t	0	1	1	A, B
t+1	t+1	t+1	0	0	0	A, B, C

2.3.5 Frequency Combining

Despite the very high stability currently achieved by individual cesium beam frequency standards, there are always applications which would benefit from increased stability. Increased stability can be achieved by averaging the outputs of a number of individual cesium standards. One method is a system which mechanizes this averaging by purely digital means.

A digital frequency combiner operates by comparing the phase of the output with the phase of each input. When the relative phases of the input and output have changed by a fixed amount, a frequency correction is applied to the output voltage controlled oscillator. A block diagram of a digital frequency combiner is shown in Figure 2-7. The circuitry inside the dashed rectangle is repeated for each input atomic standard, whereas the other circuitry is common to the whole system.

Beginning with the internal quartz crystal oscillator, the output sine wave is squared to drive both the countdown chain and the delay line. The countdown chain provides all timing signals for the system. The delay line is used to break the internal 5 MHz clock signal into multiple phases, one for each tap of the delay line. Once each 200 micorseconds, and always referenced to the same point in the input signal, a pulse is generated by the strobe control logic. This pulse is used to shift the phase of the internal clock into the present phase storage register while the old contents are shifted to the past phase storage.

The input clock and the internal clock slowly drift apart in phase. Eventually the past and present phases will differ by one. This is detected by the incremental phase difference logic, and the phase accumulator is either incremented or decremented by one. The contents of this digital accumulator are converted into an analog voltage for frequency correction of the internal crystal oscillator. This method of frequency combining provides a true average frequency of all of the clocks. If a clock is

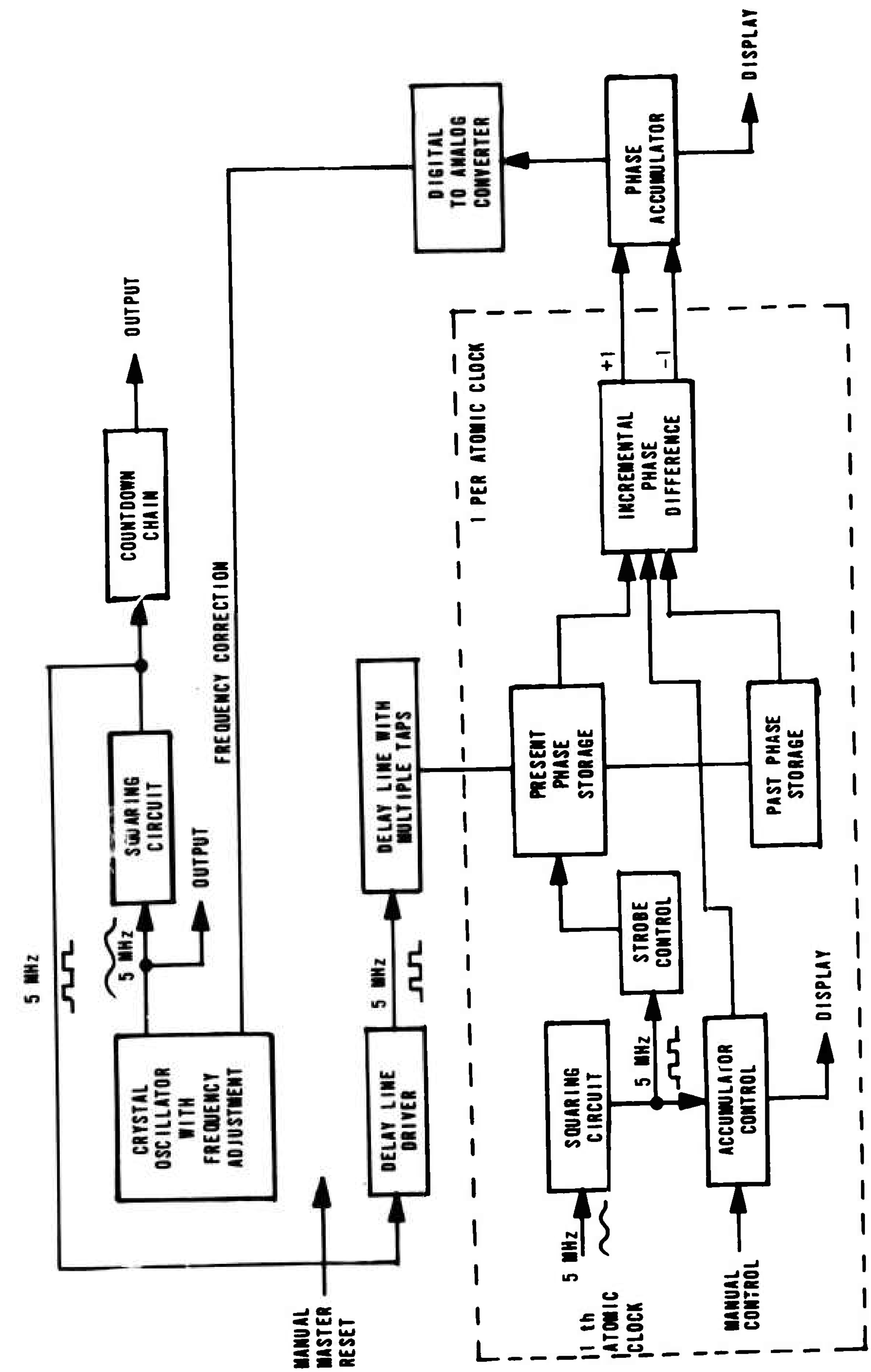


FIGURE 2-7 BLOCK DIAGRAM OF FREQUENCY COMBINER

connected or disconnected, the average frequency of the clocks changes accordingly.

Frequency combining in this manner is practical to implement. However, it is questionable that the increased cost is justificable for only two clocks. This is particularly so because the system as shown in Figure 2-5 has a high availability just by having a second standard available for use.

2.3.6 Conclusions

Multiple frequency standards can be used to provide both better long term stability and improved system availability by having another standard readily available. A time/frequency standard availability of at least 0.999895 can be obtained with two cesium beam standards and a Loran-C monitor for a backup. The only limitation is that a fault must be identified or removed within 1/2 hour. Various monitoring techniques can identify faults within a few seconds. Frequency averaging could be implemented, but the requirement probably does not justify the cost.

3.0 LORAN-C ACCURACY AND COMPARISONS

The objectives of this analysis are to determine time accuracy attainable by monitoring Loran-C transmission, discuss means of improving Loran-C operation relative to CAS requirements, and to compare Loran-C time accuracy with other time dissemination services. Five potential Loran-C improvements are described herein. The principal improvement is to include a data message containing USNO to Loran-C time offset. Loran-C time accuracy is compared with two-way satellite, TV, and WWV and WWBV time accuracy. Loran-C accuracy is better than WWV and TV, worse than satellite accuracy, and comparable to WWVB's potential time accuracy.

3.1 LORAN-C TIMING ACCURACY

The timing accuracy attainable by monitoring Loran-C signals is a function of (1) time offset from USNO; (2) reduction of errors by a portable clock visit; (3) anomalies in the propagation path; and (4) equipment stability. The timing accuracy of the received Loran-C signal is 0.2 to 0.3 microseconds, 1 σ. The primary limitation is anomalies in the atmosphere which affect signal propagation velocity.

3.1.1 Loran-C Background (Potts, Ref. 9)

Loran-C is primarily a long-range, precision, hyperbolic navigation system which is made up of several chains of stations. Each chain consists of a master and two or more slaves. Within each chain the master transmits; then at fixed times later, the slaves transmit. Receiving stations can determine their own location from the differences in time of arrival of these signals.

Location accuracy is a function of the time synchronization between master and slaves. Cesium beam frequency standards, which are installed at all Loran-C stations, provide the timing precision necessary for navigation. By setting the frequency standards to a convenient scale, currently A_1 frequency, Loran-C transmissions become a reliable frequency reference and can also be synchronized to UTC time (as maintained by the USNO and Coast Guard).

3.1.2 Loran-C Error Budget

The various error terms involved are defined in Table 3-1; one sigma error estimates are assigned as appropriate.

TABLE 3-1 LORAN-C ERROR TERMS

Definition	Error Term	1σ Estimate
Known difference between UTC time and Loran-C time at master	σ_{ut}	0.28 us(2)*
System error (transmitter, receiver, antenna, cables, etc.)	σ_{se}	0.3 us(3) *
Path length prediction error	σ_{pe}	0.4 us (3)*
Ground wave propagation anomaly over land	σ_{gpa}	0.2 us (3)
Ground wave propagation anomaly over water	σ_{gps}	0.1 us (3)
Airwave propagation anomaly (one hop)	σ_{apa}	4.0 us (3)
Synchronization error between Loran-C master and slave	σ_{ss}	0.05 us (3)
User Measurement error	σ_{me}	0.05 us(4)

* Can be minimized by a visit of portable clock.

(2) Potts and Wieder Ref. 10

(3) Pakos Ref. 3

(4) Stone, Ref. 11

3.1.3 Error Calculation

Assuming all of the error terms from Table 3-1 are independent, the error is predicted as follows:

$$\sigma_t = [\sigma_{ut}^2 + \sigma_{se}^2 + \sigma_{pe}^2 + (\sigma_{gpa}^2 \text{ or } \sigma_{apa}^2 \text{ or } \sigma_{gps}) + \sigma_{ss}^2 \pm \sigma_{me}^2]^{1/2} \tag{3-1}$$

If all terms are used unconditionally and without traveling clock or USNO support, the 1σ error is 0.586 μs, 0.611 μs, or 4.04 μs depending upon the use of the ground wave over seawater or land, or the sky wave for timing. If conditions are controlled, some of the terms can be reduced. Specifically if the user can wait until the daily time offset [UTC USNO versus Loran-C] has been measured, σ_{ut} can be replaced by σ_{utm}, the USNO measurement accuracy term of 0.1 μs. Assuming uniform distribution (σ = max. value/$\sqrt{12}$), the new 1σ value of σ_{utm} is 0.03 μs. Further, assume that the station has been visited by a portable clock which is used to calibrate system errors and the propagation prediction error. Accordingly, σ_{se} and σ_{pe} can be replaced by σ_c (calibration term) whose value can be determined from paragraph 1.1.2. Assume σ_c maximum value is 0.01 μs.

Since σ_{apa} (airwave propagation anomaly) is large, it is clear that only the ground wave (over land or over seawater) should be used to monitor CAS ground station time.

Accordingly, $$\left[\sigma_t = \sigma_{utm}^2 + \sigma_c^2 + (\sigma_{gpa}^2 \text{ or } \sigma_{gps}^2) + \sigma_{ss}^2 + \sigma_{me}^2\right]^{1/2} \tag{3-2}$$

For the above error estimates

$$\sigma_t = \{(0.00\ 833)^2 + (0.01)^2 + [(0.2)^2 \text{ or } (0.1)^2] + (0.05)^2 + (0.05)^2\}^{1/2}\ \mu s \tag{3-3}$$

σ_t = 0.123 μs over seawater or 0.213 μs over land

$3\sigma_t$ = 0.37 μs over seawater or 0.64 over land

3.1.4 Propagation Anomaly Reduction

The largest single term in equation 3-3 is the propagation anomaly. There are two practical approaches to minimizing this error; monitor multiple Loran-C stations, and synchronize clocks relative to a common Loran-C station.

3.1.4.1 Multiple Loran-C Stations

The propagation anomaly is caused primarily by diurnal and seasonal variations, weather disturbances, etc., which affect the conductivity of the ground wave propagation path. The dielectric constant and the index of atmospheric refraction are also affected but to a lesser degree. These changes cause variations in the effective propagation path. If an additional Loran-C transmission can be monitored, it is possible to reduce the propagation anomaly. However, it is necessary that propagation paths be uncorrelated. Therefore, the Loran-C stations must not be located along common bearing relative to the receiving stations. Assuming that the paths are independent, the magnitude of the propagation anomaly can be reduced inversely proportional to the square root of the number of Loran-C stations being monitored.

3.1.4.2 Relative Loran-C Synchronization

If it is necessary to trace time back to the USNO, all of the error sources of equation 3-2 must be considered. However, if the requirement is that the time differences between adjacent CAS ground stations should be minimized, then relative synchronization to a common Loran-C station is potentially acceptable. For this case, only the propagation anomaly and the measurement error affect the time error where the expected value of the time difference is expressed as follows:

$$\varepsilon_t = (\varepsilon_{P1} - \varepsilon_{P2}) + (\varepsilon_{r1} - \varepsilon_{r2}) \tag{3-4}$$

where ε_{P1} is the path anomaly, and ε_{r1} is the receiver noise,

$$\sigma_{\varepsilon g}^2 = (\varepsilon_{P1}^2 + \varepsilon_{P2}^2 - 2\varepsilon_{P1}\,\varepsilon_{P2}) + (\varepsilon_{r1}^2 + \varepsilon_{r2}^2 - 2\varepsilon_{r1}^2\,\varepsilon_{r2} - + 2(\varepsilon_{P1} - \varepsilon_{P2})(\varepsilon_{r1} - \varepsilon_{r2}) \tag{3-5}$$

Since ε_{r1} and ε_{r2} are uncorrelated, this reduced to

$$\sigma_{\varepsilon t}^2 = (\sigma_{P1}^2 + \sigma_{P2}^2 - 2\sigma_{P1}\sigma_{P2}) + (\sigma_{r1}^2 + \sigma_{r2}^2) \tag{3-6}$$

This equation is difficult to evaluate because the degree of correlation of paths 1 and 2 is undefined. For the values of terms from Table 3-1, the relative time error ranges from 0.07 to 0.57 $\mu s, 1\sigma$, depending upon the degree of correlation in the propagation path. For receiving stations in the same general direction and range from the master station, the degree of correlation of the propagation paths could approach unity so that the time error can be quite small, e.g., 0.1 μs for path correlation of 0.5.

3.1.5 Loran-C as CAS Time Reference

Loran-C provides an absolute time reference which is accurate within 0.6 to 0.7 μs, 3σ and which is available almost continuously. If Loran-C is used as a CAS time reference, the time at any two ground stations would be within 1 μs, 3σ. Loran-C is the most readily available, accurate reference. There are good reasons to use Loran-C as a reference in spite of the requirement, or to relax the requirement slightly to include Loran-C. Especially since relative time accuracy referenced to Loran-C can be within 0.1 μs for a correlation value of 0.5 between the propagation paths.

3.1.6 Conclusions

Loran-C transmissions can be used to monitor time to within 0.37 μs, 3σ if the propagation path is over seawater and to within 0.64 μs, 3σ over land. The principal error term is the propagation anomaly which can be reduced by averaging the signals from more than one Loran-C station. Synchronization to a common Loran-C station may also reduce time differences between ground stations to an acceptable value.

3.2 LORAN-C IMPROVEMENTS

The objective of this analysis is to review characteristics of Loran-C and suggest ways in which it could be improved, to permit more accurate or more convenient monitoring of the time/frequency ground stations. Five potential improvements are discussed herein as to benefit to the ground stations.

3.2.1 One and Six Second Ticks

The Loran-C time scale currently operates on the UTC frequency (A1, like CAS). The USNO in their Time Service Announcement, Series 9, publishes Ephemeris tables of the Time of Coincidence between the UTC second and the master station pulse groups. The UTC second can be locally recovered with millisecond accuracy from WWV, which is more than adequate for startup of the Loran-C timing receiver. Thus, between WWV and Loran-C, time is determined to submicrosecond accuracy. Due to the use of the leap second to adjust UTC time, the relation of the CAS epoch to the minute is not constant, but it is known and could be announced in advance. These announcements pertaining to the CAS epoch could be included in the USNO Time Series publications and the National Bureau of Standards Bulletins. A complement, perhaps less susceptible to user error, is for the Loran-C master to transmit a six-second tick coincident with the start of the CAS epoch in a manner similar to the one-second tick recently abandoned for lack of users. This is only a slight modification and a restoration of a previous service.

3.2.2 USNO - Loran-C Offset

The USNO monitors the transmissions from the Loran-C master stations and issues daily TWX bulletins listing the current Loran-C offset to within 0.1 μs. The USNO and Coastguard do not attempt to control the offset closer than 5 μs (Pakos, Ref. 3). As a result, the offset can vary significantly with respect to the requirements of FAA ER-240-016. If the Loran-C master station clocks were slaved to USNO time/frequency the offset would be reduced to the value limited by propagation anomalies. This USNO - Loran-time offset is measured daily to within 0.1 μs and published in daily TWX's and weekly in the time service bulletin, "Daily Phase Values, Series 4". As a complement to better slaving, this offset could be encoded and transmitted within the Loran-C signal format. This would simplify timekeeping at the various locations.

3.2.3 Time Coding on Transmissions

Loran-C transmissions contain time and frequency information. However, it is necessary to have time to within one second in order to lock up on the Loran-C correctly. Presently, time is obtained from WWV or a cesium beam time/frequency standard. If the Loran-C transmission included a coded time word containing at least minutes and seconds, a Loran-C receiver could be set up without external time inputs.

3.2.4 Expanded Coverage

Loran-C transmissions can be heard over much of the world. However, there are notable exceptions such as the west coast of the United States. Expansion of Loran-C to include these areas or upgrading the daylight only coverage by Loran-D would improve timekeeping capabilities in these areas.

3.2.5 Loran-C Station Tolerance

Presently, the Loran-C master station blinks the ninth pulse in the group to indicate one or more of the chain stations is unusable for navigation (Potts, Ref. 9). The ninth pulse is blinked in Morse Code for the letter R (•-•) followed by one, two, three or four dots indicating the unusability of the specific slave station. The blink interval is 12 seconds. The slave stations blink their first two pulses (on 0.25 seconds, off 3.75 seconds) when usuable. Current models of Loran-C receivers do not detect this blinking. Therefore, an out of tolerance condition is not readily detected. If the receivers were able to detect the pulse blinking, it would aid in station timekeeping.

3.3 TIME SYNCHRONIZATION USING A SYNCHRONOUS SATELLITE

Time transfer accuracy using a satellite is a function of the communication link characteristics and whether a one-way or two-way communication is used for the time transfer. Time transfer using one-way transmissions must include allowances for both satellite and ground equipment location errors and propagation anomalies. These errors are effectively cancelled out with two-way transmissions because of signal path reciprocity. The attainable time transfer accuracy by satellite is 0.1 to 10 μs, 1σ depending upon the method used, effective use of the communication link, and calibration errors.

3.3.1 Satellite Time Transfer Background

Satellites have been used in time transfer experiments for several years. Their principal advantage is in providing a line-of-sight relay between two widely spaced ground stations. Line-of-sight path lengths can be calculated more precisely than ground wave paths. Two basic approaches to satellite time transfer are used: one-way transmissions, and two-way transmissions. Two-way transmissions are used, where better accuracy is required, to minimize the uncertainty in path lengths caused by ground station and satellite location errors. If a single frequency is used, two-way transmission eliminates the uncertainty in the signal propagation velocity caused by variations in the ionosphere and troposphere. However, the two-frequency interrogate transpond satellites currently in use have a small residual error because of non-reciprocity. Many of the satellites in current use are part of the Defense Communication Satellite Systems. Consequently, they are not readily available for civilian use.

3.3.2 Error Budget

The various error terms and 1 σ error estimates are listed in Table 3-2.

TABLE 3-2 SATELLITE SYNCHRONIZATION ERROR BUDGET

Error Source	Term	1σ Error (μ sec)
Measurement of Transmitter delay (slave, satellite, or master)	$\sigma_{ts}, \sigma_t \sigma_{tm}$	0.05(a)
Measurement of receiver delay (slave, satellite, or master)	$\sigma_{rs}, \sigma_{rss}, \sigma_{rm}$	0.05(b)
Ground Station Location (slave or master)	$\sigma_{ls} \sigma_{lm}$	0.7(c)
Satellite Location	σ_{lss}	1.5(c)
Propagation effects in ionosphere	σ_{pi}	6.0(c)
Propagation effects in troposphere	σ_{pt}	0.3(c)
Noise jitter	σ_{nj}	0.01(b)
Time measurement error	σ_{me}	0.01(d)

(a) Assuming transmitter and receiver delays variations are equal

(b) Osborne, Ref. 12

(c) Gatterer, et al, Ref. 13

(d) Using reasonably high speed logic

3.3.3 Error Calculation

There are two basic approaches to disseminating time via satellite: (1) one-way transmission where the master transmits and the slave receives, and (2) two-way transmissions where both the master and slave transmit and receive. The first method is shown in Figure 3-1. The master transmits to the satellite which retransmits to the slave. In this case, all the error sources listed in Table 3-2 contribute to the time error. However, if the second method is used as shown in Figure 3-2, some of the error terms can be eliminated. Assume that the master station transponds to a slave station transmission, although other timing techniques are also valid. The time, t_{sm}, at which the slave's signal arrives at the master indicated in equation 3-6.

$$t_{sm} = t_s + D_{ts} + t_{pss} + D_{rss} + D_{tss} + t_{psm} + D_{rm} \tag{3-6}$$

where

t_s is slave time at start of transmission

D_{ts} is the slave transmitter delay including σ_{ts}

t_{pss} is propagation time slave to satellite including σ_{ls}, σ_{lss}, σ_{pi}, and σ_{pt}

D_{rss} is the satellite receiver delay including σ_{rss}

D_{tss} is the satellite transmitter delay including σ_{tss}

t_{psm} is propagation time satellite to master including σ_{lss}, σ_{lm}, σ_{pi}, and σ_{pt}

D_{rm} is the master receiver delay including σ_{rm}

Likewise a signal transmitted from the master at time, t_m will arrive at the slave at time, t_m will arrive at the slave at time, t_{ms}.

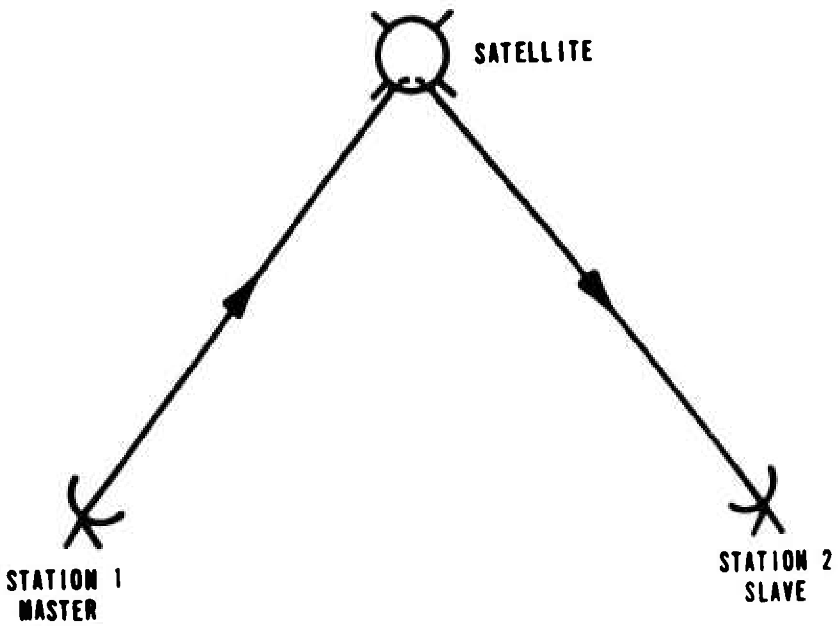


FIGURE 3-1 ONE-WAY TIME TRANSFER

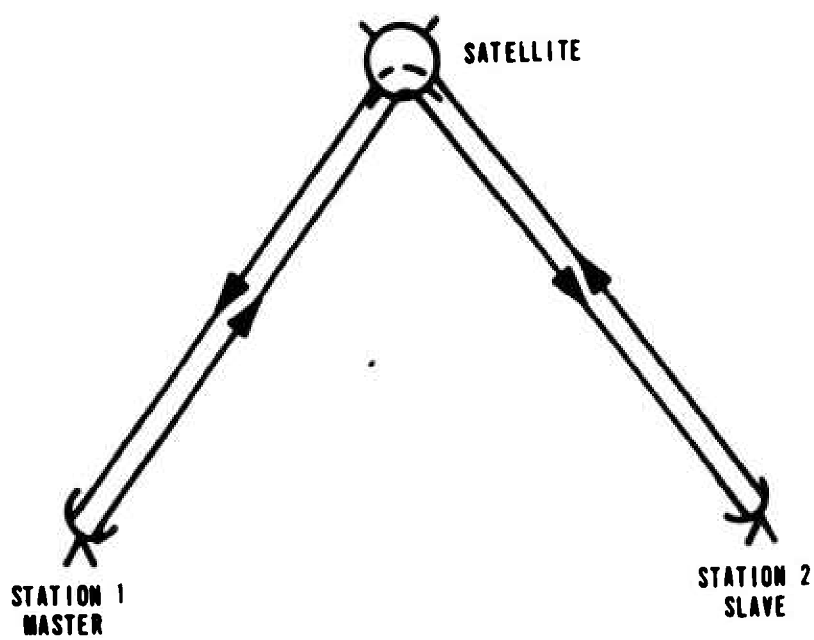


FIGURE 3-2 TWO-WAY TIME TRANSFER

$$t_{ms} = t_m + D_{tm} + t_{psm} + D_{rss} + D_{tss} + t_{pss} + D_{rs} \qquad (3\text{-}7)$$

where

D_{tm} is the master transmitter delay including σ_{tm}

D_{rs} is the slave receiver delay including σ_{rs}

If t_{sm} (3-6) is subtracted from t_{ms} (3-7)

$$(t_{ms} - t_{sm}) = (t_m - t_s) + (D_{tm} - D_{ts}) + [t_{pms}(\text{up link})$$

$$-t_{pms}\,(\text{down link}] + [t_{pss}\,(\text{down link}) - t_{pss}\,(\text{up link})]$$

$$+(D_{tss} - D_{tss}) + (D_{rss} - D_{rss}) + (D_{rs} - D_{rm}) \qquad (3\text{-}8)$$

If the entire communication link is one frequency, the propagation path delays, up link versus down link, are equal and the bracket terms cancel each including all uncertainties. However, if up link and down link are on different frequencies as is typical in satellite time transfers, a new term replaces the t_{pii} terms in 3-8. This uncertainty, $\sigma_{nr} = 0.1$ μs [Jesperson, et al, Ref. 14], is caused by the non-reciprocity of the propagation times due to frequency difference. Furthermore, the satellite transmitter and receiver delays, D_{tss} and D_{rss} cancel except for their noise jitter [$(D_{tss} - D_{tss}) = (D_{rss} = D_{rss}) = 2\,\sigma_{nj}$]. Master and slave transmitter and receiver delays can be measured except for their noise. Equation 3-8 is written in terms of its variances.

$$\sigma_t = (2\sigma_{me}^2 + \sigma_{tm}^2 + \sigma_{ts}^2 + \sigma_{nr}^2 + \sigma_{rs}^2 + \sigma_{rm} + 4\sigma_{nj}^2)^{1/2} \qquad (3\text{-}9)$$

Where $2\sigma_{me}$ is added to include the time measurement uncertainty at the master and at the slave.

$$\sigma_{tm} = \sigma_{ts} = \sigma_{rs} = \sigma_{rm} \text{ therefore} \qquad (3\text{-}10)$$

$$\sigma_t = (2\sigma_{me}^2 + 4\sigma_{tm}^2 + \sigma_{nr}^2 + 4\sigma_{nj}^2)^{1/2} \qquad (3\text{-}11)$$

The noise jitter, σ_{nj}, is a function of signal to noise and link bandwidth (BW). For a 10 MHz bandwidth, σ_{nj} is negligible for any ratio of signal power to noise power greater than 30 dB as demonstrated by the following calculation (Skolnik, Ref. 19):

$$\sigma_{nj} = \frac{1}{BW\ (2S/N)^{1/2}} = \frac{1}{10^7 (2x1000/1)^{1/2}} = 0.7 \text{ ns} \qquad (3\text{-}12)$$

Therefore, for strong signals,

$$\sigma_t = (2\ \sigma_{me}^2 + 4\ \sigma_{tm}^2 + \sigma_{nr}^2)^{1/2} \qquad (3\text{-}13)$$

The measurement uncertainty, σ_{me}, can be minimized with high speed logic. For 100 MHz counting σ_{me} = 0.01 μs. The transmitter and receiver delay uncertainty is difficult to establish because it must include transient environmental effects. Osborne (Ref. 15) uses 0.05 μs for this term assuming many calibrations during each time transfer. This leaves the non-reciprocity term σ_{nr} = 0.1 μs (Jesperson, et al, Ref. 13) as the predominate term.

$$\sigma_t = (2 \times 0.01^2 + 4 \times 0.05^2 + 0.1^2)^{1/2} = 0.141 \text{ μs} \qquad (3\text{-}14)$$

3.3.4 Conclusions

Time transfer via satellite can be within 0.42 μs, 3σ provided two-way transmissions are used, the communication link is used effectively, and the equipment is calibrated.

3.4 TELEVISION TIME TRANSFER ACCURACY

Timing accuracy attainable by monitoring TV signals is a function of

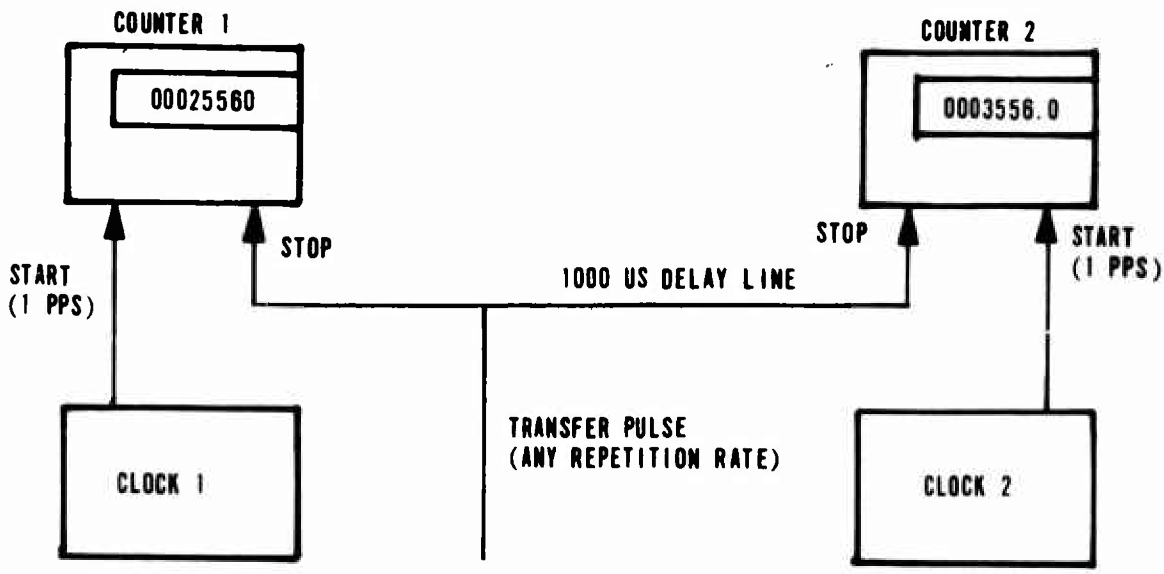
(1) The accuracy of the TV station clock relative to USNO time,
(2) Cable and microwave routing of the TV network,
(3) Need for real time vs. "after-the-fact" time synchronization, and
(4) Absolute versus relative time sync.

Time accuracy by TV monitoring can be within 1.03 μs provided strict calibration procedures are used.

3.4.1 TV Time Transfer Background (Davis, et al, Ref. 16)

For an introduction to clock comparison, consider two clocks side by side in the same laboratory, each one connected to a digital counter as shown in Figure 3-3. When the 1-pps time ticks from both clocks are coincident, counters 1 and 2 will start at the same instant. Now, with a 1000 μs delay line connected between the stop inputs, the received transfer pulse will stop counter one 1000 μs before counter two. The actual counter readings have no real significance; however, the difference in readings will be a constant 1000 μs. Conversely, a known delay would enable synchronization of clocks that may not be on time. It is possible to transfer this basic concept to precise clocks separated by several kilometers but within the service area of the same television transmitter. Once the radio propagation path has been calibrated, the television timing system can be used to compare two or more clocks quite readily.

Extending the clock-comparison system one step further, Figure 3-4 gives the basic concept of the TV line-10 differential delay system. At the same time of day to the nearest second, counters are started with a 1-pps tick from their local atomic clocks. Close to this time, a horizontal sync pulse is broadcast from one of the originating television transmitters in New York City. After diverse delays through both common and separate microwave links, the sync pulse is received (live) at different times and stops the appropriate counters. As in the two-clock situation in one laboratory, the difference between each pair of counter readings remains constant within the bounds of propagation delay stability of the distribution mediums and gives an accurate comparison between clocks. Similarly, any laboratory can compare its clocks with NBS and USNO time scales through use of a duplicate reception system



CASE 1 (LAB): COUNTER 2 - COUNTER 1 = 3556.0 US - 2556.0 US = 1000 US

CASE 2 (TV): COUNTER 2 - COUNTER 1 = DIFFERENTIAL PATH DELAY + CLOCK DIFFERENCE (2 RELATIVE TO 1)

FIGURE 3-3 BASIC CLOCK COMPARISONS WITH DELAY LINES

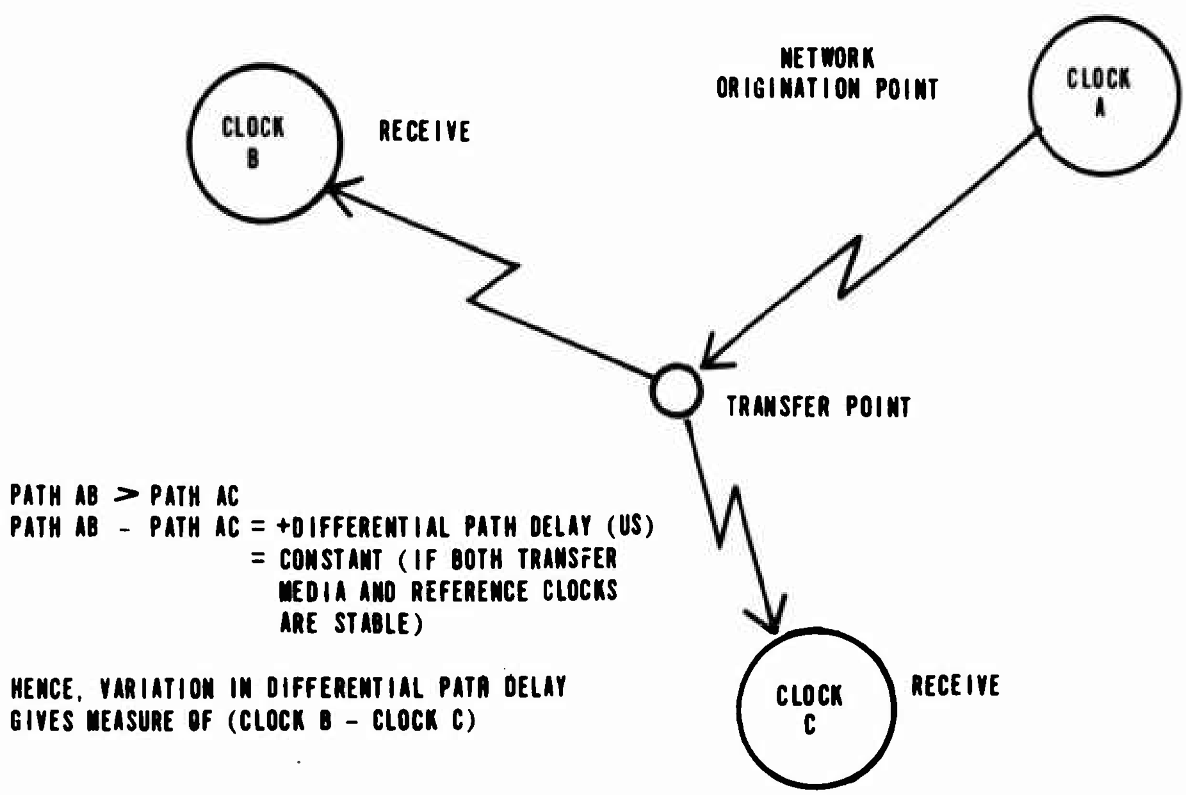


FIGURE 3-4 CONCEPT OF TELEVISION LINE-10 DIFFERENTIAL MEASUREMENTS

once the clock has been initially compared with a master clock and the propagation path delay has been calibrated. (Note that the clocks must be accurate to within one television picture frame or approximately 30 ms for this system to be useful.)

3.4.2 TV Sync Error Budget

The various error terms involved in non-disciplined TV network synchronization are identified in Table 3-3,

TABLE 3-3 TV SYNC ERROR TERMS

Definition	Error Term
Difference between UTC time and TV station clock	σ_{ut}
TV cable routing change	σ_{cc}
System error (transmitter, receiver, cables, antenna, etc.)	σ_{se}
Path length prediction error	σ_{pe}
Path length propagation anomaly	σ_{pa}
User measurement error	σ_{me}

3.4.3 Error Calculations

Assuming all of the error terms of Table 3-3 are independent, the error prediction is as follows:

$$\sigma_t = [\sigma_{ut}^2 + \sigma_{se}^2 + \sigma_{pe}^2 + \sigma_{pa}^2 + \sigma_{cc}^2 + \sigma_{me}^2]^{1/2} \tag{3-15}$$

If some of the conditions can be controlled, some of these error terms can be reduced significantly or eliminated. Specifically, assume that the user can check with the USNO on a daily basis to determine the offset of the originating station clock. The term σ_{ut} can then be replaced by a measurement error term σ_{utm} of 0.1 μs, 1σ. Assume also that the user has obtained the USNO versus TV time difference measurement. Then cable routing changes can be identified and accounted for providing they exceed the daily clock drift rates. Therefore, assume σ_{cc} = 1.0 μs. If the station has been visited by a portable clock, the system error and prediction error can be replaced by a calibration term, σ_c, whose value is established in paragraph 1.1 as 0.2 μs ($1\sigma = 0.2/\sqrt{12}$.

TABLE 3-4 TV SYNC ERROR BUDGET

Error Term	1σ Estimate
σ_{utm} (replaces σ_{ut})	0.3 μs
σ_{cc}	1.0 μs
($\sigma_{pe} + \sigma_{se}$) after clock visit	0.07 μs
σ_{pa}	0.2 μs
σ_{me} (high speed logic)	0.01 μs

The error equation now becomes

$$\sigma_t = [\sigma_{utm}^2 + \sigma_{cc}^2 + (\sigma_{pe} + \sigma_{se})^2 + \sigma_{pa}^2 + \sigma_{me}^2]^{1/2} \qquad (3\text{-}16)$$

For the error values from Table 3-4, the 1σ error using TV time sync is 1.02 μs.

3.4.4 Relative TV Time Synchronization

The preceding discussion traces time synchronization back to the USNO. It is also possible to synchronize clocks relative to each other via a common TV transmission without regard to the absolute time. The procedure is precisely the same as described previously in paragraph 3.4.1 except the originating station is ignored and the relative time of arrival between the two receiving stations is the only important measurement. For this case equation 3-15 reduces to

$$\sigma_t = \sqrt{2}\,[\sigma_{pe}^2 + \sigma_{pa}^2 + \sigma_{me}^2 + \sigma_{ci}^2]^{1/2} \qquad (3\text{-}16a)$$

where σ_{co} is the offset between the clocks at each station and $\sqrt{2}$ accounts for the fact the measurement is the difference in time between two locations. The value of σ_{co} can be quite large, however, it can be minimized by a visit from a portable clock. Therefore, σ_{co} can reasonably be assigned a value of 0.1 to 0.2 μs. The propagation paths, within the area of a television transmission are highly correlated. Since major networks are essentially independent, the standard deviations of each time error can be combined optimally by weighting each one inversely proportional to its variance (Allan, et al, Ref. 17). The magnitude of each weighting term (α_1) is calculated from the following equation which is derived in the Appendix.

$$\alpha_1 = \frac{\frac{1}{\sigma_1^2}}{\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} + \cdots + \frac{1}{\sigma_i^2}} \qquad (3\text{-}17)$$

Under these circumstances, the time stability is essentially limited to 5 to 10 μs for short periods of time (one half hour) by the stabilities of the network and local oscillators. (IEEE, Ref. 18). For times of several weeks, relative time can be maintained to the submicrosecond level.

3.4.5 Conclusion

Accurate time can be obtained by monitoring network TV programs at the same time as the USNO is monitoring the programs. Individual station readings have no value in themselves but become significant only when compared to the USNO readings. Absolute time accuracies of about 1 μs, 1σ can be attained with TV monitoring; relative time accuracy can be maintained to within less than 1 μs over several weeks and by within 10 μs for one half hour.

3.5 TIME SYNCHRONIZATION FROM WWV (NBS FREQUENCY AND TIME BROADCASTING SERVICES, REF. 19

WWV transmits time and frequency signals on carrier frequencies of 2.5 to 25 MHz. The skywave is used, except within 100 miles of the transmitter, because of this time transfer accuracy is limited to about 4 μs, 1σ for most users.

3.5.1 WWV Background

WWV transmits both frequency and time which have been coordinated with the Bureau Internation de L'Heure (BIH), Paris, France. The transmissions are based upon the international time scale, Universal Coordinated Time (UTC). WWV transmits on 5 different carrier frequencies 2.5, 5, 10, 20, and 25 MHz. Transmission frequencies and times are held constant, as nearly as possible, with the National Bureau of Standards (NBS) in Boulder, Colorado.

At frequencies in the 3 to 25 MHz band and at distances greater than 100 miles, transmission depends chiefly on skywaves reflected from the ionosphere (Reference data for Radio Engineers, Ref. 20). This is a region where the rarified air is sufficiently ionized to reflect or absorb radio waves. The effects are controlled by the free electron density. The ionosphere is usually considered as consisting of four layers:

(1) D layer 50 - 90 kilometers (km) in daylight only;
(2) E layer 110 km;
(3) F_1 layer 175-250 km in daylight only; and
(4) F_2 layer 250 - 400 km (principal reflective layer).

3.5.2 WWV Error Budget

The pertinent error terms for time transfer with WWV are defined in Table 3-5 along with 1 σ error estimates.

TABLE 3-5 WWV ERROR TERMS

Term Definition	Error Term	1σ Estimate
Difference between UTC (USNO) time & WWV time	σ_{ut}	0.07 μs*
System error (transmitter, receiver, antenna, etc.)	σ_{se}	0.3 μs
Path length prediction error	σ_{pe}	0.1 μs*
Ground wave propagation anomaly	σ_{gpa}	0.2 μs
Skywave propagation anomaly	σ_{spa}	4.0 μs
User measurement error (high speed logic)	σ_{me}	0.01 μs

* After visit by portable clock.

3.5.3 Error Calculation

The principal error source in using WWV signals for time synchronization is the variation in path length which depends upon a reflection from the ionosphere. The approximate magnitude of this variation is determined as follows:

Figure 3-5 shows the path of a signal between points on the earth's surface via a one-bounce skywave. The actual path through the ionosphere is curved; however, the curved path is approximately equal to the triangular path TAR (Ionospheric Radio Propagation, Ref. 21) which can be determined from Figure 3-6 and the law of cosines.

$$p = 2\,[R^2 + R + H)^2 - 2\,R\,(R + H)\cos\theta/2]^{1/2} \qquad (3\text{-}18)$$

where R is the effective earth's radius which is 4/3 actual radius (Jansky and Bailey, Ref. 22).

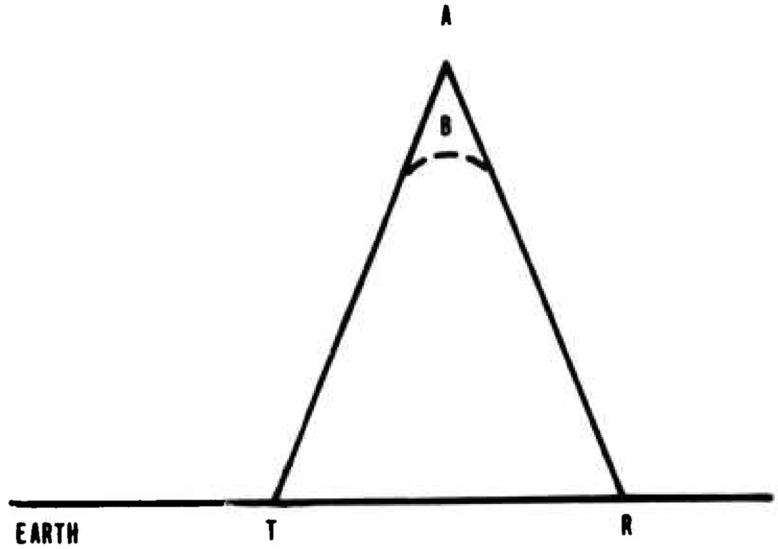


FIGURE 3-5 SKYWAVE PATH

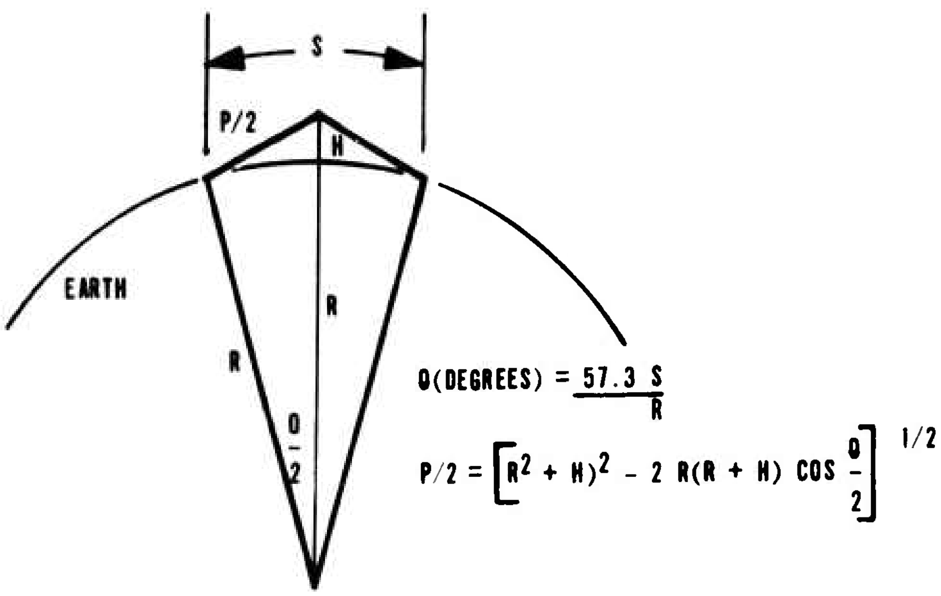


FIGURE 3-6 SKYWAVE PATH CALCULATION

$$dp = \frac{2\ [2\ (R + H) - 2\ R \cos\ \theta/2]dH}{2\ [R^2 + (R + H)^2 - 2\ R\ (R + H)\ \cos\ \theta/2]}{}^{1/2} \tag{3-19}$$

$$dp = \frac{2\ [R\ (1-\cos\ \theta/2 + H]\ dH}{[2\ R^2\ (1-\cos\theta/2) + 2\ RH\ (1-\cos\theta/2) + H^2]}\ {}^{1/2} \tag{3-20}$$

Using R (radius of the earth) equals 6,378 kilometers and a fixed ground path of 1,609 km, equation 3-20 reduces to

$$dp = \frac{(76.06 + 2H)}{(64{,}683.3 + 76.06\ H + H^2)^{1/2}} \tag{3-21}$$

The average altitude and altitude variation of the four reflective layers in the ionosphere are listed in Table 3-6.

TABLE 3-6 ALTITUDE OF IONOSPHERIC LAYERS

LAYER	AVERAGE ALTITUDE (Kilometers)	MAXIMUM ALTITUDE VARIATION (Kilometers)	1σ VARIATION (Maximum/√ Kilometers)
D	70	20 (Ref. 1)	5.77
E	110	25 (Est.)	7.22
F_1	212.5	37.5 (Ref. 1)	10.83
F_2	325	75 (Ref. 1)	21.65

Solving equation 3-21 for the altitudes and altitude variations of Table 3-5 and converting the altitude variation to a time variation yields 1σ time errors ranging from about 5 μs (D layer) to about 60 μs (F_2 layer). The frequency difference between WWV and Loran-C has no significant effect upon the velocity of propagation, therefore, these results are consistent with the 50 μs uncorrected skywave accuracy of Loran-C (Potts, Ref. 9). However, the major portion of this error is caused by diurnal, (particularly sunrise and sunset), and seasonal variations. Therefore, the effects of these variations can be reduced by sampling at the same optimum time each day. A time error of 4 μs, 1σ is used for the accuracy of Loran-C skywave (Pakos, Ref. 3).

3.5.4 Conclusions

WWV provides accurate time transfer used if the receiving station is within the reach of the ground wave, about 100 miles. However, at greater ranges the time transfer accuracy is limited by the skywave to about 4 μs.

3.6 WWVB TIME TRANSFER ACCURACY

Timing accuracy attainable by monitoring WWVB signals is a function of WWVB time offset relative to USNO; (2) a visit by a portable clock to minimize bias errors; (3) anomalies in the propagation path; and (4) equipment stability. The timing accuracy of the received WWVB signal is 0.5 μs, 1σ. The principal limitation is the propagation anomaly which may be reduced if a different frequency traversing the same path can be monitored.

3.6.1 WWVB Background (NBS Publication 236, Ref. 23)

WWVB transmits a standard radio frequency, standard time signals, time intervals, and UTC corrections. WWVB identifies itself by advancing its carrier phase 45° at 10 minutes after every hour and returning to normal phase at 15 minutes after the hour. WWVB can also be identified by its unique time code which is described in detail in Ref. 23. WWVB broadcasts a standard radio carrier frequency of 60 kHz with no offset from A1. It also broadcasts a time code consistent with the internationally coordinated time scale UTC(NBS). The frequency of WWVB is normally within its prescribed value to better than 2 parts in 10^{11}. Deviations from day to day are less than 1 part in 10^{12}.

The WWVB time base is derived from the basic frequency of a Cesium (Cs) Atomic Beam. This standard is used to calibrate the oscillators, dividers and clocks which generate the controlled frequency and the NBS time scales. The Fort Collins WWVB master clock is compared on a daily basis with the NBS master clock by using the line-10 horizontal synchronizing pulses from a Denver television station. All other clocks and time-code generators at the Fort Collins site are then compared with the Fort Collins master clock. Frequency corrections of the WWVB and WWVL quartz crystal oscillators are based on their phase relative to the NBS master clock.

3.6.2 WWVB Error Budget

TABLE 3-7 WWVB ERROR TERMS

Definition	Error Term	Error Estimate
NBS to USNO offset	σ_{ut}	5μs Max. (Ref. 24)
WWVB to NBS offset	σ_{vb}	0.16 μs (a)
System error (Transmitter, receiver antenna, cables, etc.)	σ_{se}	0.3 μs (b) (Est.)
Path length prediction error	σ_{pe}	0.4 μs (b) (Est.)
Propagation anomally (ground wave)	σ_{pa}	0.5 μs (Ref. 17)
User measurement error	σ_{me}	(Included in σ_{pa})(c)

(a) Daily phase deviation per current issue of Ref. 23.

(b) Can be minimized by portable clock visit.

(c) σ_{pa} is a measured value which includes both path and instrument deviations.

3.6.3 Error Calculation

Assuming the errors in Table 3-7 are independent, the total time can be expressed as follows:

$$\sigma_t = (\sigma_{ut}^2 + \sigma_{vb}^2 + \sigma_{se}^2 + \sigma_{pe}^2 + \sigma_{pa}^2)^{1/2} \qquad (3\text{-}22)$$

If it is necessary to make an instantaneous time error estimate, all of the terms in 3-22 must be used at their values in Table 3-6. However, daily checks with either USNO or NBS can reduce σ_{ut} to 0.1 μs, 3σ. Furthermore, a visit by a portable clock can reduce the combined value of σ_{se} and σ_{pe} to 0.2 μs, 3σ. This new value is defined as σ_c. Equation 3-22 now becomes

$$\sigma_t = [0.03^2 + 0.15^2 + 0.07^2 + 0.5^2]^{1/2} = 0.5\ \mu s \qquad (3\text{-}23)$$

3.6.4 Discussion

The principal difference between WWVB timing accuracy and Loran-C timing accuracy is caused by the value assigned to the propagation anomaly, σ_{pa}. This difference may be attributed to insufficient data on the WWVB transmissions, and an adverse propagation path for the test analyzed (Boulder, Colorado to Palo Alto, California). Allan and Barnes (Ref. 25) use measured values of WWVB (60 kHz) and WWVL (20 MHz) phase variations to analyze the propagation path from Boulder, Colorado to Palo Alto, California. Their analysis indicates that the cross-correlation coefficient between 20 kHz and 60 kHz was not zero. Using a weighted combination of the two transmissions reduced the apparent level of flicker phase noise by a factor of 2.7 for WWVB and 11.4 for WWVL. Allan and Barnes assumed that the flicker noise (propagation anomaly) was large enough to swamp the other error sources. However, if two frequencies are available and flicker noise reduction techniques are used, these other error sources must be included in the error analysis.

3.6.5 Conclusions

WWVB transmissions provide time transfer information which is potentially accurate to within 0.2 μs, 1σ (comparable to Loran-C) The limited amount of data available is over a mountainous path which has 0.5 μs, 1σ error. However, if another frequency, such as WWVL, can be monitored and results are correlated, it is possible to reduce the phase error by appropriate combinations of the two measurements such as described in the Appendix.

4.0 CAS MONITORING REQUIREMENTS

An important criterion for any CAS concept is the operational confidence in the system. TF/CAS has several inherent features which remove many of the constraints placed on the failure warning and functional test/monitoring techniques in other ground and airborne systems. TF/CAS is a time-ordered cooperative system in which each participant automatically reports updated information. These features provide numerous possibilities for types and levels of internal and external tests/monitoring. The analysis of these features is divided into four sections: test type identification/description, tests in the CAS equipment, CAS alert level, and testing the CAS signal in space. The first section establishes some requirements for tests, and identifies dypes and groups of tests. The second section lists the tests included in the CAS design and identifies these tests according to the criteria of the first section. The third section describes specific failure criteria for each of the degradation monitors. The last section identifies and describes specific means to test the CAS signal in space.

4.1 TEST TYPE IDENTIFICATION/DESCRIPTION

Before test analysis can begin, some form of classification is needed to identify and define the various types, groups and levels of tests and monitoring functions. The first part of this section identifies and describes two basic types of tests. The second part expands these two tests into groups of tests associated with specific types of equipment. The last part describes levels of tests to which parameters are monitored.

4.1.1 Types of Tests

Two types of tests are defined herein: (1) those tests which the system makes a decision and takes action; and (2) those tests in which the system makes a decision, provides an indication but does not take action.

Type I - Those tests in which the system makes a decision and takes an action which shuts down, inhibits, or modifies the operation of the system. These tests may be fully automatic and usually do not require a "man-in-the-loop". These tests are usually continuous, but may be intermittent when the system has several modes of operation. Examples of these tests are:

(a) Challenge and respond

(b) Command and respond

(c) Power/signal monitor (fault requires action), and

(d) Comparison monitor (fault requires action)

Type II - those types of tests in which the system makes a decision and provides an output, but does not inhibit the use of the system in any way. These tests are, therefore, not fully automatic and require a "man-in-the-loop". The tests are usually not continuous in that an operator must interpret the results of the test and take the required action. The outputs provided by the system may or may not be continuously available.

Type II tests are generally variations of Type I tests listed above, but the control and/or interpretation of the results (usually displayed) are performed by the pilot, operator or maintenance personnel. Examples of these tests are:

(a) Press-to-test (lamp test, manual test)

(b) Dynamic monitors (power, range, message, readouts)

(c) Comparison monitors (redundant displays for added confidence in the information)

(d) Difference monitors (readout of magnitude or error)

(e) GO/NO-GO monitors (alarms, lamps, meters)

4.1.2 Groups of Tests

If the two types of tests are associated with the ground and airborne CAS subsystems, and if one station is considered as "test equipment" and the "test specimen" (unit under test), there are four possible tests. If self testing is permitted, there are four more tests. These eight tests are combined into two new groups of four:

Ground Station Initiated CAS Tests

(1) Type I self test

(2) Type II self test

(3) Type I test of airborne CAS

(4) Type II test of airborne CAS

Airborne Station Initiated CAS Tests

(1) Type I self test

(2) Type II self test

(3) Type I test of ground station

(4) Type II test of ground station

These groups can be further expanded by considering if the test is initiated by man or by machine. The resulting sixteen conditions are listed in Table 3-1. Tests may then be classified in terms of "mode" of operation as shown. Note that Type I tests may be either automatic or semi-automatic; they cannot be totally manual. Type II tests can be either semi-automatic or manual; they cannot be fully automatic. Self tests and cooperative tests can be of any type of mode (automatic, semi-automatic, or manual).

While there are 16 different types of tests described in Table 4-1, some tests are clearly impractical. Specifically one station should not be permitted to shut down another without operator intervention. This limitation eliminates four tests from consideration: 5, 6, 13 and 14.

4.1.3 Levels of Tests/Monitored

There are three levels of tests or degrees to which any performance parameters are monitored. These levels are:

(1) Accuracy of Calibration - Generally, a monitor cannot assess operational system accuracy, unless it is part of the system. In the case of the ground station, each clock is indeed a part of the subsystem, and its accuracy can be traced to the U.S.N.O. master clock.

GROUND STATION INITIATED CAS TESTS

Test Identification	Test Type	Test Mode	Test Initiated by G/S	Final Action Taken By	Comment
1	I	Automatic	Equipment	G/S Equipment	Self Test
2	I	Semi-Auto.	Operator	G/S Equipment	Self Test
3	II	Semi-Auto.	Equipment	G/S Operator	Self Test
4	II	Manual	Operator	G/S Operator	Self Test
5	I	Automatic	Equipment	A/S Equipment	G/S Tests A/S
6	I	Semi-Auto.	Operator	A/S Equipment	G/S Tests A/S
7	II	Semi-Auto.	Equipment	A/S Operator	G/S Tests A/S
8	II	Manual	Operator	A/S Operator	G/S Tests A/S

AIRBORNE INITIATED CAS TESTS

Test Identification	Test Type	Test MOde	Test Initiated by G/S	Final Action Taken By	Comment
9	I	Automatic	Equipment	A/S Equipment	Self Test
10	I	Semi-Auto.	Operator	A/S Equipment	Self Test
11	II	Semi-Auto.	Equipment	A/S Operator	Self Test
12	II	Manual	Operator	A/S Operator	Self Test
13	I	Automatic	Equipment	G/S Equipment	A/S Tests G/S
14	I	Semi-Auto.	Operator	G/S Equipment	A/S Tests G/S
15	II	Semi-Auto	Equipment	G/S Operator	A/S Tests G/S
16	II	Manual	Operator	G/S Operator	A/S Tests G/S

NOTES: G/S = ground station
A/S = airborne station
Operator may be crew or maintenance personnel

TABLE 4-1 TEST TYPE AND DESCRIPTION

(2) GO/NO-GO Monitor - Most tests, of the operational system, monitor and indicate when GO/NO-GO conditions exist. It is expected that system performance is significantly better than the monitor limits. However, level or failure indication must be on the safe side and inhibit the function or remove information which is marginally faulty. A suitable alarm or flag is implied.

(3) Degradation Monitor - Continuous readout and caution alarms can aid in the prevention of catastrophic failures. When used in this way, degradation monitors are a maintenance tool. This level of monitor may also be used to change the operational mode of the system so that it remains safely in service at reduced performance. For example, if ground station time degrades beyond the 0.5 microsecond accuracy requirement, it is possible and safe to operate it like an aircraft on the ground in hierarchy mode. In fact, the demotion rate logic used in airborne CAS is a degradation monitor with 63 steps. The last step forces the CAS to backup mode (BUM) when provided, or to standby when not provided.

4.2 TESTS/MONITORING IN PRESENT DESIGN

This section is divided into two parts. The first part lists and describes the tests and categorizes the tests according to the criteria of Paragraph 4.1.2. The second investigates the relative significance of each of these tests.

4.2.1 Test Definition

Testing, monitoring and the use of Built-in-Tests (BIT) are part of the basic maintenance philosophy. Table 4-2 contains a list and description of each test currently being incorporated into the CAS equipment. Table 4-2 also classifies the tests as to type, mode, etc. Column 2 lists a test identification number which corresponds to the numbers in the first column of Table 4-1 and identifies the test type, mode, etc.

TESTS INCLUDED IN CAS EQUIPMENT TABLE 4-2

Test	Test Type	Test Description
Ramp Test	12	Simulated ranges, range rates, and altitudes are transmitted by master so aircraft can verify that their CAS is operating within safe limits.
Skew Test	7	Checks for aircraft with out-of-sync (skewed) time slots
System Status/ Control	4	Compares LORAN-C receiver and cesium clocks.
Time Tick Comparison (6sec,0.1ms)	1	Verifies that corresponding time ticks occur within 0.5 us of each other.
Forward Power	1,9	Monitor measures forward transmitted power and activates if power exceeds threhold (approx. 500 watts).
Reverse Power	1,9	Monitor measures reflected RF power. If reverse power exceeds threshold (approx. 200 watts), the monitor causes immediate shutdown.
Transmitter	1,9	If pulse modulator duty is excessive (pulse width or repetition rate), high power modulation is inhibited.
Range Pulse	1,9	Range pulse modulation is tested. Four consecutive failures of any of the normal pulse width checks results in a BIT failure.
Epoch	1,9	Ground epoch start triad modulation is tested to check format.
Resync Triad	1,9	Ground resync triad is generated in response to non-zero range modulation signal in test slot. Triad is checked.
Basic Timing	1,9	The 10 MHz and own basic timing counter are monitored. If monentary or prolonged dropout occurs, BIT is failed.
Biphase Modem	1,9	Receiver demodulates leakage from own transmissions and passes signal to logic as NRZ-Leveld data for bit-by-bit comparison with original logic signal.
Receiver Sensitivity	3,11	Logic commands Exciter to generate 25 MHz signal in test slot 1612. Signal causes step recovery diode in Rcvr Monitor to produce 1600 MHz pulse (level approx-80dBm) which is coupled into receiver front end. Logic tests normal receiver threshold video output for weak signal sensitivity

TESTS INCLUDED IN CAS EQUIPMENT(Cont) TABLE 4-2

Test	Test Type	Test Description
Master/Slave Loop	1,9	Transmitted epoch start triad from master channel is received by slave (via antennas). Thresholded video in slave is verified & returned to master logic comparison circuit.
Overvoltage	1,9	If transmitter high voltage supply senses overvoltage condition, signal is routed to lockout pulse modulator to protect transmitter.
Pin Diode Protection	1,9	Malfunction in receiver monitor (receiver switch pin diode limiter circuit), such as loss of bias voltage, causes lockout of pulse modulator to protect pin diode and receiver.
Exciter Duty	1,9	Locks out transmitter RF drive if logic pregate signal exceeds normal maximum duty.
Master Transmission Monitor	4	Slave channel display is used to monitor master transmissions.
RF Power-DC Voltage Monitor	4	Panel mounted meter used for manual checks of indicated signals.
Sync Transmit Monitor	3	Verify Sync triads are transmitted.
Overheat	9	Turns off power (except to fan) when the temperature in the low voltage power supply exceeds a preset value.
Antenna Open	9	Turns off power if an open circuit is sensed on an antenna.
oscillator Adjust	11	Indicates if oscillator has been adjusted to its limit in either direction.
Biphase Test	3,11	Verifies that logic correctly converts NRZ-level data to NRZ-space data for biphase modulation.
Doppler	11	Test to see that Doppler measurements are within specified limits.
ATCRBS Fail	9	Invalid altitude inputs.
Power Off	9	No power on internal power bus.
Lamp Test	4	Verifies lamps are operative.
FBS Lamp Test	12	Verifies lamps are operative.
Time Difference Display	16	Checks time difference between FBS unit and ground station.
FBS Fail	11	Verifies that ground station to CAU time difference is within specified tolerance.
Sync Received Light	11	Verifies that sync signals are being received in the selected slot.

4.2.2 Test Evaluation

Table 4-2 contains a list of tests/monitoring in present CAS equipment. The relative significance of each test is evaluated in Table 4-3, by applying the pertinent questions to each test. While many questions might be considered, they must generate variable answers for different tests to be useful. The following five questions were answered relative to each test. Based upon this evaluation, the biphase test (logic only) is of questionable value.

(1) Safety - does the test prevent hazards and/or secondary failures? (yes, 1; no, 0; create hazards, -1)

(2) Maintainability and availability - does the test assist maintainability and increase availability? (yes, 1; no, 0)

(3) Effectiveness - does the test assess the effects of a failure on the end performance of the CAS or does it measure an intermediate parameter? (end item, 1; intermediate, 0; insignificant, -1)

(4) Probability - does the test or monitor detect reasonably probable failures and malfunctions which can result in operationally significant degradation or performance?

(5) Indicators - does the failure or degradation indicator bring the problem to the attention of the proper personnel? (yes, 1; no, 0)

4.3 CAS ALERT LEVEL

The objective of this section is to identify the level or type of degradation which will cause the CAS tests to fail. Table 4-4 is a list of each CAS test followed by the failure criteria. The sequence of tests is the same as in Tables 4-2 and 4-3.

4.4 CAS SIGNAL-IN-SPACE MONITOR

The objective of this analysis is to review the nature of external monitoring used to check the operation of airborne CAS signals in space

TABLE 4-3 TEST VALUE ANALYSIS

Test	Guidelines					
	Safety	Maintainability & Availability	Effectiveness	Probable Error	Indicators	Sum
Ramp Test	1	0	1	1	1	4
Skew Test	1	0	1	1	1	4
System Status Control	0	1	1	1	1	4
Time Tick Comparison	1	1	1	1	1	5
Forward Power	1	1	0	1	1	4
Reverse Power	1	1	0	1	1	4
Transmitter Modulation	1	1	0	1	1	4
Range Pulse	0	1	0	1	1	3
Epoch	0	1	0	1	1	3
Resync Triad	0	1	0	1	1	3
Basic Timing	1	1	1	0	1	4
Biphase Modem	0	1	0	0	1	2
Receiver Sensitivity	0	1	0	1	1	3
Master-Slave Loop	0	1	0	1	1	3
Overvoltage	1	1	0	1	1	4
Pin Diode Protection	1	1	0	1	1	4
Exciter Duty Cycle	1	1	0	1	1	4
RF Power-DC Voltage Monitor	1	1	0	1	1	4
Sync Transmit Monitor	0	1	0	1	1	3
Overheat	1	0	0	1	1	3
Antenna Open	1	1	0	1	1	4
Oscillator Adjust	1	1	0	1	1	4
*Biphase Test (Logic)	0	1	-1	0	1	1
Doppler	1	1	1	1	1	5
ATCRBS Fail	1	1	0	0	1	3
Power Off	0	0	0	1	1	2
Lamp Test	0	1	0	1	1	3
FBS Lamp Test	0	1	0	1	1	3
Time Difference Display	0	0	1	1	1	3
FBS Fail	0	0	0	1	1	2
Sync Received Light	0	1	0	1	1	3

* Questionable Value

TABLE 4-4 TEST FAILURE CRITERIA

Test	Failure Criteria
Ramp Test	0.2 nm range error, 100 knots doppler error, or 300 feet altitude error.
Skew Test	Misalignment equal to or greater than 1 us.
System Status/Control	Cesium standards or Loran difference exceeds 0.5us
Time Tick Comparison (6 sec, 0.1 ms)	Misalignment of greater than 0.5 us.
Forward Power	Forward power less than 500 watts.
Reverse Power	Reverse power greater than 200 watts.
Transmitter	Duty cycle exceeds 5%.
Range Pulse Epoch Triad Resync Triad	Any video dropout during video present test; or any video during video absent test; or a 1 μs error. However, the epoch and resync triad tests must fail four consecutive tests to activate fail indicator.
Basic Timing	Loss of one or more clock counts.
Biphase Modem	Four consecutive bit errors.
Receiver Sensitivity	Receiver does not detect a 0-80 dBm signal.
Master/Slave Loop	One bit failure activates Bit indicator.
Overvoltage	Voltage generated by the high voltage power supply rises above 4,000 volts.
Pin Diode Protection	Loss of bias voltage or current.
Exciter Duty	Exciter duty cycle exceeds 5%.
Master Transmission Monitor by Slave Channel	0.2 nm range error; 100 knots doppler error; or 300 feet altitude error.
RF Power-DC Voltage Monitor	Forward power less than 500 watts nominal; reverse power more than 400 watts nominal; or voltage + 10% of nominal.
Sync Transmit Monitor	0.1 us error in sync transmit time.
Overheat	Low voltage power supply temp exceeds 245°F.
Antenna Open	Open circuit on antenna(s).
Oscillator Adjust	Adjust counter reads.
Biphase Comparison	Error in one or more bits.

TABLE 4-4 TEST FAILURE CRITERIA (Cont)

Test	Failure Criteria
Doppler	0 ± 0.4 Vdc for zero knot test; 2 ± 0.4 Vdc for 500 knot test.
ATCRBS Fail	Open circuits on both altitude failure warning inputs to CAU or detection of all ones for all zeros on C1, C2, and C4 ATCRBS bit inputs.
Power Off	No voltage on one or more internal buses.
Lamp Test	Lamp fails to illuminate.
FBS Lamp Test	Lamp(s) fail to illuminate.
Time Difference Overflow	Time difference exceeds 9.99 us.
FBS Fail	5 MHz or 1 pulse/6 second lines disconnected or time base error exceeds 0.5 us.
Sync Received Light	No sync signal received.

while the aircraft is on the ground. Three tests from Section 3.1 fall into this category: skew, data message display (range, range rate, altitude, and biphase) and data message exchange. Each of these tests is described herein.

4.4.1 Skew Test

There are two types of skew. in-slot and out-of-slot. In-slot skew is defined as skew greater than 1 us but less than 1 ms. Out-of-slot skew is defined as skew greater than 1 ms and includes the possiblity of time being apparently "synchronized" but wrong by an integer number of slots.

In-slot skew monitoring/detection is performed by the slave channel of the ground station. The slave channel transmits sync requests, in vacant slots, to the aircraft in air epochs. The slave channel monitors the sync response and displays the aircraft slot number if the sync response is received outside the normal sync window. The slave channel checks each aircraft sequentially, starting with the lowest number. The slave channel checks as many aircraft as possible each epoch, consistent with the transmitter duty cycle limitation.

Out-of-slot skew is monitored/detected passively by listening to each transmission and comparing ground station slot number with the slot number received in the data transmission from the aircraft. In normal operation, transmission frequency is changed every message slot to one of four frequencies. If an aircraft is skewed out of slot, it has 1 chance in 4 of being off frequency also. Therefore, the slave channel listens for 6 consecutive seconds on each frequency and repeats the same frequency every twenty-four seconds. This ensures that aircraft which are skewed out-of-slot are heard. Biphase and altitude information from the responding aircraft are displayed and used (1) to identify the aircraft; (2) to determine if the aircraft is skewed; or (3) to determine if the aircraft is in backup mode (BUM).

4.4.2 Display Panel

While the aircraft are on the ground, the slave channel of the ground station monitors aircraft's transmissions. Both received data and measured data are displayed on the monitor panel. After takeoff aircraft altitude and the biphase data are displayed along with measured range and range rate. These data are used to verify message content and to aid in identifying time-skewed aircraft.

4.4.3 Data Message Exchange

A 4-bit octal message can be generated by the ground station and sent to the fly-by sync aircraft. The fly-by sync panel is also capable of generating a similar 4-bit octal message. By prearrangement, the ground station could transmit a message which is recreated by the fly-by sync aircraft and transmitted back to the ground station thereby checking both the up link and the down link. Non-fly-by sync aircraft do not have this capability.

APPENDIX

Derivation of Coefficients for Combining Independent Correlated Standard

Derivation:

$$\tau = \alpha_1\tau_1 + \alpha_2\tau_2 + \alpha_3\tau_3 \qquad \text{(A-1)}$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \qquad \text{(A-2)}$$

$$\tau^2 = \alpha_1^2\tau_1^2 + \alpha_2^2\tau_2^2 + \alpha_3^2\tau_3^2 + 2\,[\alpha_1\alpha_2\tau_1\tau_2 + \alpha_1\alpha_3\tau_1\tau_3 + \alpha_2\alpha_3\tau_2\tau_3] \qquad \text{(A-3)}$$

$$\sigma_\tau^2 = E\tau^2 = \alpha_1^2\sigma_{\tau_1}^2 + \alpha_2^2\sigma_{\tau_2}^2 + \alpha_3^2\sigma_{\tau_3}^2 \qquad \text{(A-4)}$$

$$\sigma_\tau^2 = \alpha_1^2\alpha_{2_1}^2 + \alpha_2^2\alpha_{\tau_2}^2 + \alpha_3^2\alpha_{\tau_3}^2 + \lambda\,(\alpha_1 + \alpha_2 + \alpha_3 - 1) \qquad \text{(A-5)}$$

$$\frac{\partial\sigma_\tau^2}{\partial\alpha_1} = 2\alpha_1\sigma_{\tau_1}^2 + \lambda \qquad \text{(A-6)}$$

$$\frac{\partial\sigma_\tau^2}{\partial\alpha_2} = 2\alpha_2\sigma_{\tau_2}^2 + \lambda \qquad \text{(A-7)}$$

$$\frac{\partial\sigma_\tau^2}{\partial_{\alpha_3}} = 2\alpha_3\sigma_{\tau_3}^2 + \lambda \qquad \text{(A-8)}$$

$$\frac{\partial\sigma_\tau^2}{\partial\lambda} = \alpha_1 + \alpha_2 + \alpha_3 - 1 \qquad \text{(A-9)}$$

To minimize set A-6, A-7, A-8 and A-9 equal to zero.

Subtract A-6 from A-7, and A-8 from A-7

$$2\alpha_2\sigma_{\tau_2}^2 - 2\alpha_1\alpha_{\tau_1}^2 = 0$$

$$\alpha_1 = \alpha_2\alpha_{\tau_2}^2 / \sigma_{\tau_1}^2 \qquad \text{(A-10)}$$

$$2\alpha_2\sigma_{\tau_2}^2 - 2\alpha_3\alpha_{\tau_3}^2 = 0 \qquad \text{(A-11)}$$

$$\alpha_3 = \frac{\alpha_2\sigma_{\tau_2}^2}{\sigma_{\tau_3}^2}$$

Substitute A-10 and A-11 into A-9

$$\alpha_2\left(\frac{\sigma_{\tau_2}^2}{\sigma_{\tau_1}^2} + 1 + \frac{\sigma_{\tau_2}^2}{\sigma_{\tau_3}^2}\right) - 1 = 0 \qquad \text{(A-12)}$$

$$\alpha_2 = \frac{1}{\left(\frac{\sigma_{\tau_2}^2}{\sigma_{\tau_1}^2} + 1 + \frac{\sigma_{\tau_2}^2}{\sigma_{\tau_1}^2}\right)\frac{\sigma_{\tau_2}^2}{\sigma_{\tau_2}^2}} \qquad \text{(A-13)}$$

$$\alpha_2 = \frac{\frac{1}{\sigma_{\tau_2}^2}}{\frac{1}{\sigma_{\tau_1}^2} + \frac{1}{\sigma_{\tau_2}^2} + \frac{1}{\sigma_{\tau_3}^2}} \qquad \text{(A-14)}$$

The other coefficients are derived similarly.

DEFINITION OF TERMS

A1	Atomic Time
ATCRBS	Air Transport Control Radar Beacon System
BIT	Built-In-Test
CAS	Collision Avoidance System
dBm	Decibels Referenced to one Milliwatt
DC	Direct Current
FBS	Fly-By Sync
ms	Millisecond
nm	Nautical Mile
NRZ Level	Non-Return to Zero Level
NRZ Space	Non-Return to Zero Space
ns	Nanosecond
RF	Radio Frequency
S/N	Signal to Noise Ratio
Sync	Synchronous, Synchronize
USNO	United States Naval Observatory
UTC	Universal Time Coordinated
Vdc	Volts, Direct Current
μs	Microsecond
σ	Standard Deviation

REFERENCES

(1) G.M.R. Winkler, "Recent Experiment of Flying Atomic Clocks, Loran-C, Omega, VLF for Clock Synchronization"; Report to XVII General Assembly Warsaw 1972 of the International Union of Radio Sciences; 1972. Page 1.

(2) F. H. Reder and G.M.R. Winkler, "IRE Transaction on Military Electronics", April - July 1960, Page 366.

(3) P. E. Pakos, "Use of LORAN-C System for Time and Frequency Dissemination", Frequency Technology, July 1969, pp 13-18.

(4) F. Mosteller, R. E. K. Rourke, and G. B. Thomas, Jr. "Probability with Statistical Applications": Massachusetts: Addison-Wesley Publishing Co., Inc., 1961, pp 330-1.

(5) G.M.R. Winkler, R. G. Hall, and D. B. Percival, "The U.S. Naval Observatory Clock Time Reference and Performance of a Sample of Atomic Clocks", International Journal of Scientific Metrology, Vol. 6, No. 4, Oct. 1970, pp 126-134.

(6) C. S. Stone, "Loran-C for Time and Frequency", Austron Application Note 168-3, p 19.

(7) MIL-HDBK-217A, page 8-11.

(8) I. Bazovsky, "Reliability Theory and Practice", Prentice-Hall, Inc. Englewood Cliffs, N.J., 1961, pp 100-101.

(9) C. E. Potts, "Precise ime and Time Interval (PTTI) Dissemination via the Loran-C System", Proceedings from PTTI Stragegic Planning Meeting, Volume I, December 10-11, 1970, pp 32-54.

(10) C. E. Potts and B. Wieder, "Precise Time and Frequency Dissemination via the Loran-C System"; IEEE Special Issue on Time and Frequency, May 1972, pp 530-539.

(11) Ref. 3, Page I-10.

(12) E. F. Osborne, "Global Timing Systems of Nanosecond Accuracy Using Satellite References", Technical Memorandum from John Hopkins University, Applied Physics Lab, October 1969, pp 29-32.

(13) L. E. Gatterer, P. W. Bottone, A. H. Morgan, "Worldwide Clock Synchronization using Synchronous Satellite", IEEE Trans. on Instr. and Meas., Vol. IM-17, No. 4, December 1968, pp 372-378.

(14) J. L. Jesperson, C. Kamas, L. E. Gatterer, P. F. MacDoran, "Satellite VHF Transponder Time Synchronization", Proc. of IEEE, Vol. 56, No. 7, July 1968, pp 1202-1206.

(15) M. I. Skolnik, "Introduction to Radar Systems", McGraw-Hill 1962, pp 467.

(16) D. D. Davis, B. E. Blair, J. F. Barnaba, "Long-Term Continental US System via Television Networks", IEEE Spectrum, August 1971, pp 41-52.

(17) D. W. Allen, B. E. Blair, D. D. Davis and H. E. Machlan, "Precision and Accurate Remote Synchronization via Network Television Broadcasts, Loran-C, and Portable Clocks", International Journal of Scientific Metrology, Vol. B, No. 12, April 1972, pp 64-72.

(18) D. D. Davis, J. L. Jesperson, G. Kamas, "The Use of Television Signals for Time and Frequency Dissemination", Proceedings of the IEEE, Volume 58, No. 6, June, 1970, pp 931-3.

(19) NBS Special Publication 236, 1973 Edition, "NBS Frequency and Time Broadcast Services , Radio Station WWV, WWVH, WWVB, and WWVL", pp 1-8.

(20) "Reference Data for Radio Engineers". Fifth Edition ITT, pp 26-4.

(21) "Ionospheric Radio Propagation", K. Davies U.S. Dept. of Com., National Bureau of Standards Monogram 80, page 161.

(22) Jansky and Bailey, Inc., "Engineering Evaluation of the Loran-C Navigation System", Final Report, for USCG Contract No. Tcg-40547 (CG 40.502A), pp 41-42.

(23) Ref. 19, Pages 9-11.

(24) NBS Time and Frequency Services Bulletin.

(25) D. W. Allan and J. A. Barnes, "Some Statistical Properties of LF and VLF Propagation", AGARD Conference Proceedings No. 33, Phase and Frequency Instabilities in Electromagnetic Wave Propagation", (Proc. AGARD/EPC 13th Symposium) Ankara, Turkey, October 9-12, 1967, pp 219-230.

BIBLIOGRAPHY

1. L. S. Cutter and C. L. Searle, "Some Aspects of the Theory and Measurement of Frequency Fluctuations in Frequency Standards", Proceedings of the IEEE, Vol. 54, No. 2, Feb. 1966, pp 136-154.

2. R. E. Beehler, "A Historical Review of Atomic Frequency Standards", Proceedings of the IEEE, Vol. 55, No. 6, June 1967, pp 792-805.

3. R. H. Doherty, G. Hefley, and R. F. Linfield, "Timing Potentials of Loran-C", IRE, Nov. 1961, pp 1659-63.

4. R. H. Doherty and J. R. Johler, "Meteorlogical Influences on Loran-C Ground Wave Propagation", U. S. Dept. of Commerce, Office of Telecommunications, Institute for Telecommunications Sciences, Sept. 1973.

5. IEEE Special Issue on Frequency Stabilization, Feb. 1966.

6. IEEE Special Issue on Time and Frequency, 1 May 1972.

7. J. D. Lavanceau and D. Carroll, "Real Time Synchronization via Passive Television Transmission", Time Service Division, USNO.

8. A. O. McCoubrey, "A Survey of Atomic Frequency Standards", Proceedings of IEEE, Feb 1966, Vol. 54, No. 2, pp 116-135.

9. Proceedings of the Third Annual Department of Defense Precise Time and Time Interval (PTTI) Strategic Planning Meeting, 16-18 Nov. 1971.

10. Proceedings of the Fourth Annual NASA and DOD PTTI Planning Meeting, 14-16 Nov. 1972.

11. L. D. Shapiro, "Time Synchronization from Loran-C", IEEE Spectrum August 1968, pp 46-55.